International Training Workshop on

Using

Anthropometry

for

Effective Solutions

27-30 March 2000
Kuching, Sarawak
Malaysia

Organized by
Institute of Design and Ergonomics Application
Universiti Malaysia Sarawak

Sponsored by
U.S. Air Force Office of Scientific Research, Asian Office of Aerospace Research and Development (U.S. AFOSR/AOARD)

REPORT DOCUMENTATION PAGE	*Form Approved* OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YYYY)*	**2. REPORT TYPE**	**3. DATES COVERED** *(From - To)*
18-05-2000	Conference Proceedings	27-30 Mar 00, Kuching, Sarawak, Malaysia

4. TITLE AND SUBTITLE Using Anthropometry for Effective Solutions	**5a. CONTRACT NUMBER** F6256200M9022
	5b. GRANT NUMBER
	5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S) Conference Committee	**5d. PROJECT NUMBER**
	5e. TASK NUMBER
	5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Universiti Malaysia Sarawak (IDEA) 94300 Kota Samarahan Sarawak Malaysia	**8. PERFORMING ORGANIZATION REPORT NUMBER** N/A
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) AOARD UNIT 45002 APO AP 96337-5002	**10. SPONSOR/MONITOR'S ACRONYM(S)** AOARD
	11. SPONSOR/MONITOR'S REPORT NUMBER(S) CSP-001004

12. DISTRIBUTUION/AVAILABILITY STATEMENT

Approved for public release; distribution is unlimited.

13 SUPPLEMENTARY NOTES

14. ABSTRACT

Proceedings Include the Following Topics:
"Introduction to Ergonomics, Anthropometry, and User Centred Design"; "Principles and Practice of Anthropometry"; "Human Diversity";"Axiomatic Design"; "Application 1: Chair and Microscope Workstation Design" "Development of A National Anthropometric Database"; "Application 2: Footwear and Clothes Design" "Effective Anthropometry Process"; "Statistics for Anthropometry"; "Anthropometric Fit Mapping"; "Application 3: Crew Station Design"; "3-D Solutions"; "CAESAR – 3D Anthropometry Survey"; Cleopatra: A Database Management for CAESAR"; "3D Body Scanners"; "Polyworks"; "Integrate"; "Rapid Prototyping Techniques"; "Survey Process Optimization"; and "Hands-on Anthropometric Methods."

15. SUBJECT TERMS

Anthropometry

16. SECURITY CLASSIFICATION OF:			**17. LIMITATION OF ABSTRACT**	**18. NUMBE OF PAGES**	**19a. NAME OF RESPONSIBLE PERSON**
a. REPORT	**b. ABSTRACT**	**c. THIS PAGE**			Terence J. Lyons, M.D.
U	U	U	UU	327	**19b. TELEPHONE NUMBER** *(Include area code)* +81-3-5410-4409

Standard Form 298 (Rev. 8/98)
Prescribed by ANSI Std. Z39.18

INSTITUT REKABENTUK DAN APLIKASI ERGONOMIK
INSTITUTE OF DESIGN AND ERGONOMICS APPLICATION

NAMA DAN ALAMAT PENGANJUR KURSUS/ *NAME AND ADDRESS OF TRAINING PROVIDER:*

IDEA, Universiti Malaysia Sarawak, 94300 Kota Samarahan, Sarawak, Malaysia

TAJUK BENGKEL/*WORKSHOP TITLE:*

International Training Workshop on ***Using Anthropometry for Effective Solutions***

TARIKH/*DATE*: **27-30 March 2000**

TEMPAT/*VENUE*: **Merdeka Palace Hotel, Kuching, Sarawak, Malaysia**

Objektif soalselidik ini adalah untuk memastikan bengkel latihan yang ditawarkan adalah bersesuaian dengan peserta kursus. Sila isikan borang soalselidik ini dengan sejujur-jujurnya. Untuk memastikan kerahsiaan maklumat, anda tidak perlu menyatakan nama anda atau menandatanganinya.

The objective of this questionnaire is to ensure that the training workshop offered is appropriate to the participants. Kindly complete this questionnaire according to your frank assessment. To ensure confidentiality, you are not required to state your name or sign it.

MAKLUMAT UMUM
GENERAL INFORMATION

1. Nama Organisasi Peserta/*Name of Participant's Organization:*

   ____

2. Jawatan Peserta/*Job Title of Participant:*

   ____

3. Adakah ini kali pertama anda dibiayai oleh organisasi anda untuk latihan berkaitan antropometri? *Is this the first time you are sponsored by your organization for a training on anthropometry?*

   ☐ Ya/*Yes*   ☐ Tidak/*No*

Sila tanda [✓] di kotak yang sesuai
Please tick [✓] in appropriate box

ISI KANDUNGAN BENGKEL
WORKSHOP CONTENT

		Sangat Lemah *Very Poor*	Lemah *Poor*	Memuaskan *Satisfactory*	Baik *Good*	Sangat Baik *Excellent*
1.	Sejauh mana anda merasai bengkel ini telah mencapai objektifnya? *How well do you feel the workshop achieved its stated objective(s) ?*	☐	☐	☐	☐	☐

2. Bagaimana anda menilai bengkel ini dari segi kerelevanan/kebolehterapan?
How do you rate this workshop in terms of its relevancy/applicability?

		Sangat Lemah *Very Poor*	Lemah *Poor*	Memuaskan *Satisfactory*	Baik *Good*	Sangat Baik *Excellent*
a)	Isi kandungan bengkel telah memenuhi jangkaan saya. *The workshop content has met my expectations.*	☐	☐	☐	☐	☐
b)	Isi kandungan bengkel adalah relevan dengan kerja saya dan akan meningkatkan kerja saya. *The workshop content is relevant to my work and will enhance my job.*	☐	☐	☐	☐	☐
c)	Saya boleh menerapkan apa yang telah dipelajari dari bengkel ini di dalam kerja saya. *I will be able to apply what I have learnt from this workshop to my job.*	☐	☐	☐	☐	☐

Sila tanda [✓] pada kotak yang sesuai
Please tick [✓] in appropriate box

3. Bagaimana anda menilai bengkel ini dari segi kecukupan pembelajaran?
How do you rate this workshop in terms of its learning substantiality?

	Sangat Lemah *Very Poor*	Lemah *Poor*	Memuaskan *Satisfactory*	Baik *Good*	Sangat Baik *Excellent*
a) Bengkel ini telah menambahkan pengetahuan saya dan pemahaman isi kandungan, konsep dan prinsip. *The workshop has significantly increased my knowledge and understanding of the content, concepts and principles.*	☐	☐	☐	☐	☐
b) Saya rasa saya boleh melakukan kerja saya dengan lebih baik lagi kerana bengkel latihan ini. *I feel I will be able to do my job better because of this training workshop.*	☐	☐	☐	☐	☐

4. Bagaimana anda menilai bengkel ini dari segi isi kandungannya?
How do you rate this workshop in terms of its contents?

	Sangat Lemah *Very Poor*	Lemah *Poor*	Memuaskan *Satisfactory*	Baik *Good*	Sangat Baik *Excellent*
a) Liputan isi kandungan adalah menyeluruh. *The subject matter was well covered.*	☐	☐	☐	☐	☐
b) Contoh-contoh yang disampaikan adalah berguna dan membantu meningkatkan pemahaman saya. *The examples presented were useful and helped to enhance my understanding.*	☐	☐	☐	☐	☐
c) Jumlah contoh yang disampaikan adalah mencukupi. *The number of example presented were adequate.*	☐	☐	☐	☐	☐

	Sangat Lemah *Very Poor*	Lemah *Poor*	Memuaskan *Satisfactory*	Baik *Good*	Sangat Baik *Excellent*
d) Perbincangan yang mencukupi diadakan dalam bengkel. *Adequate discussions were provided during the workshop.*	☐	☐	☐	☐	☐

Sila tanda [✓] pada kotak yang sesuai
Please tick [✓] in appropriate box

PENGAJAR BENGKEL
WORKSHOP INSTRUCTORS

1. Nama Pengajar/*Name of the Instructor*

Pertama/*First:* **Professor Martin Helander**

Kedua/*Second:* **Dr Ravindra Goonetilleke**

Ketiga/*Third:* **Ms. Kathleen Robinette**

Keempat/*Fourth:* **Mr. Marc Rioux**

2. Bagaimana anda menilai bengkel ini dari segi kriteria yang berikut?
How do you rate this workshop in terms of the following criteria?

a) Bagaimana persediaan pengajar ?
How well prepared was the instructor ?

	Sangat Lemah *Very Poor*	Lemah *Poor*	Memuaskan *Satisfactory*	Baik *Good*	Sangat Baik *Excellent*
Helander	☐	☐	☐	☐	☐
Goonetilleke	☐	☐	☐	☐	☐
Robinette	☐	☐	☐	☐	☐
Rioux	☐	☐	☐	☐	☐

		Sangat Lemah *Very Poor*	Lemah *Poor*	Memuaskan *Satisfactory*	Baik *Good*	Sangat Baik *Excellent*
b)	Keseluruhan prestasi pengajar. *Instructor's overall performance.*					
	Helander	☐	☐	☐	☐	☐
	Goonetilleke	☐	☐	☐	☐	☐
	Robinette	☐	☐	☐	☐	☐
	Rioux	☐	☐	☐	☐	☐

		Sangat Lemah *Very Poor*	Lemah *Poor*	Memuaskan *Satisfactory*	Baik *Good*	Sangat Baik *Excellent*
c)	Keseluruhan pengetahuan pengajar tentang isi kandungan subjek. *Instructor's overall knowledge of the subject matter.*					
	Helander	☐	☐	☐	☐	☐
	Goonetilleke	☐	☐	☐	☐	☐
	Robinette	☐	☐	☐	☐	☐
	Rioux	☐	☐	☐	☐	☐

		Sangat Lemah *Very Poor*	Lemah *Poor*	Memuaskan *Satisfactory*	Baik *Good*	Sangat Baik *Excellent*
d)	Kemahiran penyampaian pengajar *Instructor's presentation skills*					
	Helander	☐	☐	☐	☐	☐
	Goonetilleke	☐	☐	☐	☐	☐
	Robinette	☐	☐	☐	☐	☐
	Rioux	☐	☐	☐	☐	☐

e) Kebolehan pengajar untuk menggalakkan penyertaan.
Instructor's ability to generate participation.

	Sangat Lemah *Very Poor*	Lemah *Poor*	Memuaskan *Satisfactory*	Baik *Good*	Sangat Baik *Excellent*
Helander	☐	☐	☐	☐	☐
Goonetilleke	☐	☐	☐	☐	☐
Robinette	☐	☐	☐	☐	☐
Rioux	☐	☐	☐	☐	☐

f) Pemahaman pengajar tentang situasi sebenar
Trainer's understanding of real-world situations.

	Sangat Lemah *Very Poor*	Lemah *Poor*	Memuaskan *Satisfactory*	Baik *Good*	Sangat Baik *Excellent*
Helander	☐	☐	☐	☐	☐
Goonetilleke	☐	☐	☐	☐	☐
Robinette	☐	☐	☐	☐	☐
Rioux	☐	☐	☐	☐	☐

g) Penilaian keseluruhan anda terhadap pengajar.
Your overall rating of the instructors.

	Sangat Lemah *Very Poor*	Lemah *Poor*	Memuaskan *Satisfactory*	Baik *Good*	Sangat Baik *Excellent*
Helander	☐	☐	☐	☐	☐
Goonetilleke	☐	☐	☐	☐	☐
Robinette	☐	☐	☐	☐	☐
Rioux	☐	☐	☐	☐	☐

PENILAIAN UMUM
GENERAL ASSESSMENT

1. Bagaimana anda menilai bengkel ini dari segi kriteria yang berikut?
How do you rate this workshop in terms of the following criteria?

		Sangat Lemah *Very Poor*	Lemah *Poor*	Memuaskan *Satisfactory*	Baik *Good*	Sangat Baik *Excellent*
a)	Pemahaman yang mudah *Ease of understanding*	☐	☐	☐	☐	☐
b)	Keadaan bilik dan susunatur *Layout and Sequence*	☐	☐	☐	☐	☐
c)	Pentadbiran dan perkhidmatan sokongan *Administration and other support services*	☐	☐	☐	☐	☐
d)	Kesesuaian tempat latihan *Suitability of training venue*	☐	☐	☐	☐	☐
e)	Susunan tempat duduk *Seating arrangement*	☐	☐	☐	☐	☐
f)	Makanan dan minuman *Food and refreshments*	☐	☐	☐	☐	☐
g)	Kepatutan yuran bengkel *Registration fee reasonability*	☐	☐	☐	☐	☐

2. Adakah anda akan mencadangkan rakan sekerja anda untuk mengikuti bengkel ini?
Would you recommend your colleague(s) to attend this workshop?

☐ Ya/*Yes* ☐ Tidak/*No*

Sila jelaskan/*Please explain*:

____

____

____

3. Komen keseluruhan, jika ada:
Overall comments, if any: ______________________________

____

____

____

____

____

____

____

____

Terima kasih di atas kerjasama anda
Thank you for your cooperation

INTERNATIONALTRAINING WORKSHOP

Using Anthropometry for Effective Solutions

27-30 March 2000
Merdeka Palace Hotel & Suites
Kuching, Sarawak, Malaysia

List of Participants

Name & Position	Organisation, Address & Contact Nos.
1. Norwina binti Mohd Nawawi *Associate Professor & Head*	Department of Architecture Kulliyah Of Architecture & Environmental Design International Islamic University Malaysia Jalan Gombak 53100 Kuala Lumpur Malaysia Tel: +(603) 2056 5156 Fax: +(603) 2056 4864 Email: norwina@iiu.edu.my
2. Mr. Khong Chee Weng *Lecturer*	Multimedia University Faculty of Creative Multimedia Jalan Multimedia 63100 CyberJaya Selangor Darul Ehsan Malaysia Tel: +(603) 8312 5621 Fax: +(603) 8312 5621 Email: cwkhong@mmu.edu.my
3. Dr. Rabindra Nath Sen *Professor*	Ergonomics Centre Faculty of Management (FOM) Multimedia University 63100 CyberJaya Selangor Darul Ehsan Malaysia Tel: +(603) 8312 5671 Fax: +(603) 8312 5590 Email: r.n.sen@mmu.edu.my
4. Dr. Aida L. Velasco *Dean*	Department of Industrial Engineering College of Engineering De La Salle University 2401 Taft Avenue Manila 1004 Philippines Tel: +(632) 524 0563 Fax: +(632) 524 0563 Email: coelv@mail.dlsu.edu.ph

5. Tan Yeong Khim *Engineer*	Singapore Technologies Kinetics LTD Human Resource Department No 5, Portsdown Road Singapore 139296 Singapore Tel: +(65) 470 8990 Fax: +(65) 479 5394
6. Yi Hsueh Yang	Building 51, 195-8 Sec 4 Chung Hsing Rd Chutung, Hsinchu 310 Taiwan Republic of China Tel: +(886) 3 591 8421 Fax: +(886) 3 582 9281 Email: h880033@itri.org.tw
7. Dr. Liu.Thu Hua *Professor*	Department of Industrial Design Chang Gung University 259 Wen - Hwa 1st Rd, Kwei - Shan, Tao - Yuan Taiwan Republic of China Tel: +(886) 3 328 3016 5420 Fax: +(886) 3 328 3031 Email: thliu@mail.cgu.edu.tw
8. Teoh Chee Hooi *Lecturer*	Universiti Tenaga Nasional College Of Engineering Km 7, Jalan Kajang - Puchong 43009 Kajang Selangor Darul Ehsan Malaysia Tel: +(603) 828 7264 Fax: +(603) 826 3506 Email: chteoh@uniten.edu.my
9. Rugayah bt Issa *Lecturer*	Universiti Malaysia Sabah Tingkat 9, Gaya Centre Jalan Tun Fuad Stephen Beg Berkunci No: 2073 88999 Kota Kinabalu Sabah Malaysia Tel: +(6088) 348 440 ext. 5649 Fax: +(6088) 434 902 Email: rugayah@ums.edu.my

10. Dr. Mat Rebi bin Abdul Rani *Lecturer*	Department of Manufacturing and Industrial Engineering Universiti Teknologi Malaysia 81310 UTM Skudai Johor Bahru Johor Malaysia Tel: +6 (07) 550 4850 Fax: +6 (07) 556 6159 Email: matrebi@fkm.utm.my
11. Bjorn Peters *Researcher*	VTI- Swedish National Road and Transport Research Institute SE 58195 Linkoping Sweden Tel: + 46 (13) 204 070 Fax: + 46 (13) 741 436 Email: bjorn.peters@vti.se
12. Shamsu Mohamad *Lecturer*	Faculty of Applied & Creative Arts Universiti Malaysia Sarawak 94300 Kota Samarahan Sarawak Malaysia Tel: +6 (082) 671 000 ext #78067 Fax: +6 (082) 672 314 Email: mshamsu@faca.unimas.my
13. Saiful Bahari bin Mohd Yusoff *Lecturer*	Faculty of Applied and Creative Arts Universiti Malaysia Sarawak 94300 Kota Samarahan Sarawak Malaysia Tel: +6 (082) 671 000 ext 8081/561 Fax: +6 (082) 672 314 Email: mysaiful@faca.unimas.my
14. Ravinder Singh *Engineer*	Singapore Technologies Kinetics LTD Human Resource Department No. 5 Portsdown Road Singapore 139296 Singapore Tel: +65 470 8990 Fax: +65 479 5394 Email: staengr@stkinetics.com.sg

15. Yen Ching Chiuan *Assistant Professor*	Department of Industrial Design Chang Gung University 259 Wen - Hwa 1ST Road Kwei - Shen, Tao - Yuan Taiwan Republic of China Tel: +886 (3) 328 3016 5806 Fax: +886 (3) 328 3031 Email: ccyen@mail.cgu.edu.tw
16. Terence J. Lyons *Associate Clinical Professor*	Asian Office of Aerospace Research and Development 7 - 23- 17 Roppongi Minato-Ku, 106 - 0032 Tokyo Japan Tel: +813 5410 4409 Fax: +813 5410 4407 Email: lyonst@aord.yokota.af.mil
17. Fong Wan Loong *Research Assistant*	Institute of Design and Ergonomics Application Universiti Malaysia Sarawak 94300 Kota Samarahan Sarawak Malaysia Tel: +6 (082) - 671 000 ext 474/147 Fax: +6 (082) - 672 094 Email: wlfong@mailhost.unimas.my
18. Chan Foong Yeen *Post Graduate Student*	Institute of Design and Ergonomics Application Universiti Malaysia Sarawak 94300 Kota Samarahan Sarawak Malaysia Tel: +6 (082) 671 000 ext 474/147 Fax: +6 (082) - 672 094 Email: fychan@mailhost.unimas.my
19. Yusman bin Kamaleri *Tutor*	Institute of Design and Ergonomics Application Universiti Malaysia Sarawak 94300 Kota Samarahan Sarawak Malaysia Tel: +6 (082) 671 000 ext 474/147 Fax: +6 (082) 672 094 Email: kyusman@idea.unimas.my

20. Choong Pak Choy *Sales Support Manager*	Dynamedix Sdn Bhd 15M, Jalan 1/68E Off Jalan Sentul Manis 51000 Kuala Lumpur Malaysia Tel: +(603) 957 3889 Fax: +(603) 443 0928 Email: vickilim@tm.net.my
21. Tan Hong Hong *Senior Engineer*	Hewlett Packard Singapore (Pte) Ltd 20, Gul Way Singapore 629196 Tel: +(65) 869 8474 Fax: +(65) 861 9065 Email: hong-hong_tan@hp.com
22. Richard Khoo Chee Seong *Product Engineer*	Hewlett Packard Singapore (Pte) Ltd 20, Gul Way Singapore 629196 Tel: +(65) 869 5351 Fax: +(65) 862 4532 Email: richard-cs_khoo@hp.com
23. Dr Marzuki Hj. Ibrahim *Lecturer*	Faculty of Arts and Design Universiti Teknologi Mara 40450 Shah Alam Selangor Darul Ehsan Malaysia Tel: +(603) 5516 4075 Fax: +(603) 5510 7240
24. Wan Asri Wan Mohamed *Engineer*	Perusahaan Otomobil Nasional Berhad HICOM Industrial Estate, Batu 3, P.O. Box 7100 40918 Shah alam Selangor Darul Ehsan Malaysia Tel: +(603) 511 1055 ext. 2610 Fax: +(603) 515 3008
25. Zuli' zam bin Rashid *Engineer*	Perusahaan Otomobil Nasional Berhad HICOM Industrial Estate, Batu 3, P.O. Box 7100 40918 Shah alam Selangor Darul Ehsan Malaysia Tel: +(603) 511 1055 ext. 2610 Fax: +(603) 515 3008

26. Abdul Hakim bin Mohamed Said *Engineer*	Perusahaan Otomobil Nasional Berhad HICOM Industrial Estate, Batu 3, P.O. Box 7100 40918 Shah alam Selangor Darul Ehsan Malaysia Tel: +(603) 511 1055 ext. 2610 Fax: +(603) 515 3008
27. Isradzi Sarbini Lecturer	Faculty of Applied and Creative Arts Universiti Malaysia Sarawak 94300 Kota Samarahan Sarawak Malaysia Tel: +(6082) 671000 ext. 78082 Fax: +(6082) 672314 Email: sisradzi@faca.unimas.my
28. Dr Halimahtun Mohd Khalid *Professor & Director*	Institute of Design and Ergonomics Application Universiti Malaysia Sarawak 94300 Kota Samarahan Sarawak Malaysia Tel: +(6082) 671 790 Fax: +(6082) 672 094 Email: mkmahtun@idea.unimas.my

WORKSHOP INSTRUCTORS

1. Kathleen M. Robinette *Senior Research Anthropologist*	Air Force Research Laboratory 2255 H Street Wright Patterson AFB 45433-7022, Ohio United States of America Tel: +1 (937) 255 8810 Fax: +1 (937) 255 8752 Email: kath.robinette@wpafb.af.mil
2. Marc Rioux *Principal Research Officer*	Institute of Information Technology National Research Council of Canada Ottawa, Ontario K1A 0R6 Canada Tel: +1 (613) 993 7902 Fax: +1 (613) 952 0215 Email: Marc.Rioux@iit.nrc.ca
3. Dr. Martin G. Helander *Professor*	School of Mechanical and Production Engineering Nanyang Technological University Singapore 639798 Singapore Tel: +(65) 790 6398 Fax: +(65) 791 1959 Email: mahel@ntu.edu.sg
4. Dr. Ravindra S. Goonetilleke *Associate Professor*	Department of Industrial Engineering and Engineering Management Hong Kong University of Science and Technology Clear Water Bay, Kowloon Hong Kong Tel: +(852) 2358 7109 Fax: +(852) 2358 0062 Email: ravindra@ust.hk

International Training Workshop
Using Anthropometry for Effective Solutions

Programme

Monday, 27 March

8.45 am	Introduction to the Workshop by Prof Halimahtun Mohd Khalid
9.00 am	Introduction to Ergonomics, Anthropometry, and User-centred Design by Prof Martin Helander
10.00	**Tea/coffee break**
10.30	Principles and Practice of Anthropometry by Dr Ravindra Goonetilleke
12.00	Human Diversity by Dr Ravindra Goonetilleke
12.30 pm	**Lunch**
2.00	Axiomatic Design by Prof Martin Helander
3.30	**Tea/coffee break & Group Photo session**
4.00	Application 1: Chair and Microscope Workstation Design by Prof Martin Helander
5.30	Development of A National Anthropometric Database - Discussion
6.30	End

Tuesday, 28 March

9.00 am	Application 2: Footwear and Clothes Design by Dr Ravindra Goonetilleke
10.00	**Tea/coffee break**
10.30	Effective Anthropometry Process by Ms Kathleen Robinette
11.00	Statistics for Anthropometry by Ms Kathleen Robinette
12.30 pm	**Lunch**
2.00	Anthropometric Fit Mapping by Ms Kathleen Robinette
3.30	**Tea/coffee break**
4.00	Application 3: Crew Station Design by Ms Kathleen Robinette
5.30	End

Wednesday, 29 March

9.00 am	3D Solutions by Ms Kathleen Robinette
10.00	**Tea/coffee break**
10.30	CAESAR - 3D Anthropometry Survey by Ms Kathleen Robinette
11.30	Cleopatra®: A Database Management for CAESAR by Mr Marc Rioux
12.30 pm	**Lunch**
2.00	3D Body Scanners by Mr Marc Rioux
3.30	**Tea/coffee break**
4.00	PolyWorks® by Mr Marc Rioux
5.30	End

Thursday, 30 March

9.00 am	Integrate® by Ms Kathleen Robinette
10.00	**Tea/coffee break**
10.30	Rapid Prototyping Techniques by Mr Marc Rioux
11.30	Survey Process Optimization by Ms Kathleen Robinette
12.30 pm	**Lunch**
2.00	Hands-on Anthropometric Methods by Ms Kathleen Robinette
3.30	**Tea/coffee break**
3.45	Hands-on Anthropometric Methods (continuation)
5.00	Certificate of Attendance (handout)
5.30	End

International Training Workshop

Using Anthropometry for Effective Solutions

Kathleen Robinette
Wright Patterson AFB
Ohio, USA

Marc Rioux
National Research Council of Canada
Ottawa, Canada

Martin Helander
School of Mechanical & Production Engineering
Nanyang Technological University, Singapore

Ravindra Goonetilleke
Dept of Industrial Engineering & Engineering Management
Hong Kong University of Science & Technology, Hong Kong

Monday, 27 March

Introduction to Ergonomics, Anthropometry, and User Centred Design
by Martin Helander

Principles and Practice of Anthropometry
by Ravindra Goonetilleke

Human Diversity
by Ravindra Goonetilleke

Axiomatic Design
by Martin Helander

Application 1: Chair and Microscope Workstation Design
by Martin Helander

Development of A National Anthropometric Database
Discussion

Introduction to Ergonomics, Anthropometry and User Centred Design

Martin G. Helander
School of Mechanical & Production Engineering
Nanyang Technological University
Singapore

The Interdisciplinary Approach

Table 1.1 Design problems arising from the introduction of computers in the workplace

Problem	Knowledge required to solve problem
Work posture	Biomechanics
Keying	Biomechanics
Size of screen characters	Perception, vision research
Layout of screen information	Cognitive psychology, cognitive engineering
Designing new system	Systems design and cybernetics
Environmental factors	Noise, heat stress, cold stress

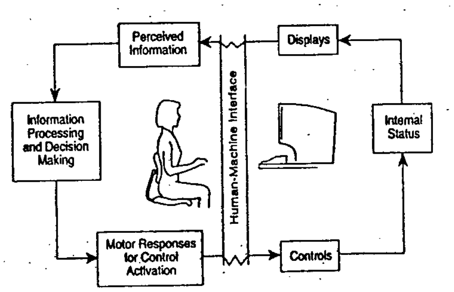


Figure 1.1 Analysis of the human-machine interface requires interdisciplinary knowledge of biomechanics, cognitive psychology and systems design methodology

The Purpose of Ergonomics is Design

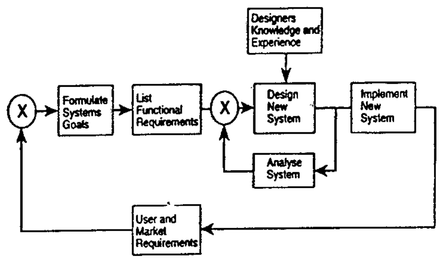


Figure 1.2 Procedure for design and redesign of a system

Applications of Ergonomics

- Defense
- Automobiles, Traffic safety
- Design of Consumer Products
- Safety and Health in Industry etc.
- Nuclear safety, Aviation and Space
- Manufacturing Productivity and Safety
- Office Ergonomics
- Human Computer Interaction
- Hand phones, E-commerce

Typical Problems in Manufacturing

Table 2.1 Ergonomic improvements at the IBM plant in Austin, Texas

1. Uniform illumination level at 1000 lux
2. Installation of special lighting for inspection
3. Job rotation to avoid monotony
4. Personal music was distracting and was discontinued
5. Ergonomic chairs certified for clean rooms
6. Improved communication
7. Materials-handling guidelines
8. Automation of monotonous jobs
9. Metric to decimal conversion charts
10. Housekeeping improved
11. Noise reduction
12. Ergonomics training
13. Continuous flow manufacturing
14. Use of protective gloves

S 200K improvement led to 7375 K gain.

Table 2.2 Projected and actual improvements

	Improvement (%)		Cost reduction ($)	
	Projected	Actual	Projected	Actual
Yield improvement	20	18	2 268 800	2 094 000
Operator productivity	25	23	5 647 500	5 213 000
Injury reduction	20	19	73 400	68 000
Total			7 989 700	7 375 000

A Reason for Anthropometry!

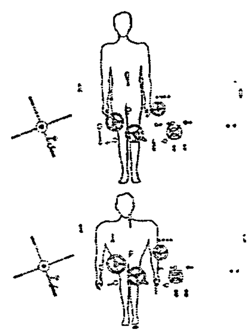


Figure 3.1 The controls of a lathe are not within easy reach of the average man. The bottom figure shows the ideal size operator (Singleton, [illegible]

Approaches in Classical Anthropometry

- Please note that there are differences in methodologies. The latter part will address the latest advances in anthropometry, which uses different methods.
- The reason that we bring up the classical methods is that they give conceptual understanding of the background problems. In addition they can be used when it is not necessary to have very exact design solutions, such as in manufacturing. They provide quick, but not necessarily dirty design solutions.

Distribution of Anthropometric Data

Table 3.1 Explanation of percentile measures

Percentile	Description
5th	5% of the population is smaller
50th	Average value
95th	95% of the population is smaller

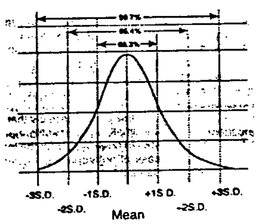


Figure 3.2 Anthropometric data are usually normally distributed

Differences in body size between people due to:

Gender
Nutrition
Genetics
Social Status?

Example of IBM San Jose Plant

Compensate for Differences by Design

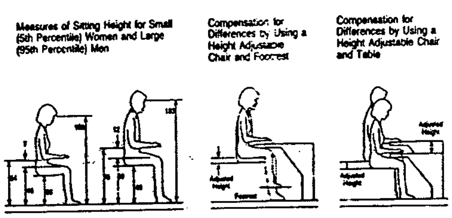


Figure 3.3 Comparison of anthropometric measures (cm) for a sitting 5th percentile female and a sitting 95th percentile male – height-adjustable chairs and tables can be used to compensate for these differences

Table 3.2 US civilian body dimensions (in cm with bare feet; add 3 cm to correct for shoes) of industrial relevance. Adapted from McConville et al. (1981)

	Female			Male		
	5th	50th	95th	5th	50th	95th
Standing						
1. Tibial height	38.1	42.0	46.0	41.0	45.6	50.2
2. Knuckle height	64.3	70.2	75.9	69.8	75.4	80.4
3. Elbow height	93.6	101.9	108.8	100.0	109.9	119.0
4. Shoulder (acromion) height	121.1	131.1	141.9	132.3	142.8	152.4
5. Stature	149.5	160.5	171.3	161.8	173.6	184.4
6. Functional overhead reach	185.0	199.2	213.4	195.6	209.6	223.6
Sitting						
7. Functional forward reach	64.0	71.0	79.0	76.3	82.5	88.3
8. Buttock–knee depth	51.8	56.9	62.5	54.0	59.4	64.2
9. Buttock–popliteal depth	43.0	48.1	53.5	44.2	49.5	54.8
10. Popliteal height	35.5	39.8	44.3	39.2	44.2	48.8
11. Thigh clearance	10.6	13.7	17.5	11.4	14.4	17.7
12. Sitting elbow height	18.1	23.3	28.1	19.0	24.3	29.4
13. Sitting eye height	67.5	73.7	78.5	72.6	78.6	84.4
14. Sitting height	78.2	85.0	90.7	84.2	90.6	96.7
15. Hip breadth	31.2	36.4	43.7	30.8	35.4	40.6
16. Elbow-to-elbow breadth	31.5	38.4	49.1	35.0	41.7	50.6
Other dimensions						
17. Grip breadth, inside diameter	4.0	4.3	4.6	4.2	4.8	5.2
18. Interpupillary distance	5.1	5.8	6.5	5.5	6.2	6.8

1 in. = 2.54 cm.

Some anthropometric measures used in manufacturing

1 in. = 2.54 cm.

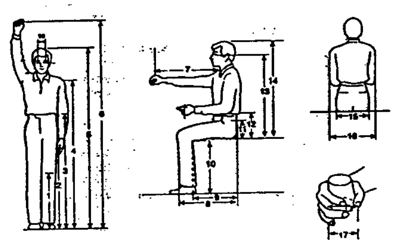


Figure 3.4 Illustration of the anthropometric measures given in Table 3.2

Different Design Principles

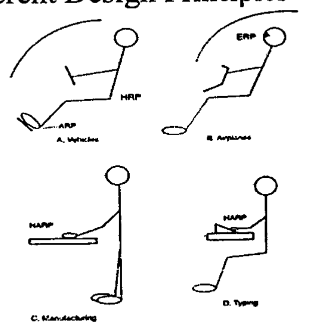


Figure 3.5 Anthropometric design can use different reference points

Calculation of Adjustability

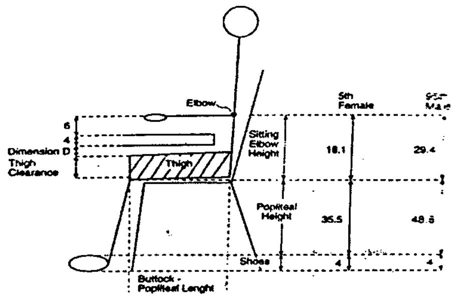


Figure 3.6 Anthropometric measures used to calculate the adjustability of seat height and table height

Exercise

Calculate Measures A, B, and C.

Design for a 5th through 95th percentile female population.

Assumptions:

1. There is no footrest.
2. The shoes are 4 cm high.
3. In the upper part of the body – from the elbows to the shoulders there is a body slump of 2 cm.
4. When looking into the microscope the operators bend the head forward about 30 degrees, which moves the position of the eyes downwards by 1.5 cm.
5. The hands are manipulating the controls at elbow height.
6. The arms are horizontal and resting on the marble slab.
7. The table top is 7.5 cm thick. The granite slab is 10 cm thick.

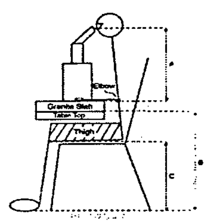


Figure 3.7 Example: designing a microscope workstation

Choice of Work Posture and Anthropometry

Table 6.1 Work postures and related complaints (Van Wely, 1970)

Posture	Complaint
Standing	Feet, lower back
Sitting without lower back support	Lower back
Sitting without back support	Central back
Sitting without proper foot support	Knees, legs, lower back
Sitting with elbows on a high surface	Upper back, lower neck
Unsupported arms or arms reaching up	Shoulders, upper arms
Head bent back	Neck
Trunk bent forward	Lower back, central back
Cramped position	Muscles involved
Joint in extreme position	Joints involved

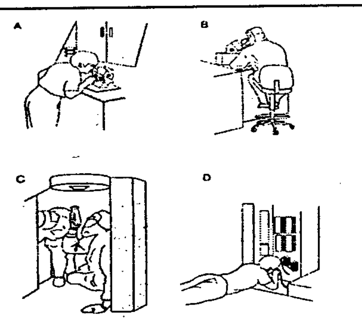


Figure 6.2 (A) The microscope is moving, and unfortunately the operator must move with it. (B) Automated manufacturing equipment – but the automation never worked fully. (C) Routine maintenance with a flashlight. (D) Final assembly of a very expensive piece of equipment

Table 6.2 Preferred work posture for different tasks

	Preferred work posture	
Type of task	First choice	Second choice
Lifting more than 5 kg (11 lb)	Standing	Sit-standing
Work below elbow height (e.g. packaging or assembly)	Standing	Sit-standing
Extended horizontal reaching	Standing	Sit-standing
Light assembly with repetitive movements	Sitting	Sit-standing
Fine manipulation and precision tasks	Sitting	Sit-standing
Visual inspection and monitoring	Sitting	Sit-standing
Frequent moving around	Sit-standing	Standing

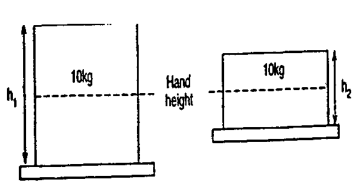


Figure 6.4 The table height is partly determined by the height of the product and the hand height (it is assumed that the products are manipulated or held at the intermediate height)

Table 6.3 Measures (cm) of preferred hand height over the floor

Type of task	Hand height = Elbow height ±	Preferred hand height over floor* (cm) Standing (5th–95th) Male	Standing (5th–95th) Female	Sitting† (5th–95th) Male	Sitting† (5th–95th) Female
Heavy lifting	−15 (Range: −20 to −10)	91–110	85–110	Not recommended	
Light assembly	−5 (Range: −10 to 0)	101–120	95–110	59–79	55–73
Typing	+3 (Range: 0 to +6)	109–128	103–118	67–87	63–81
Precision work	+8 (Range: +5 to +10)	Not recommended		72–92	68–91

*The range for females and males are 5th to 95th percentile (see Table 3.2) and were obtained by deducting or adding the value for hand height. Shoe height of 3 cm is included. 1 in. = 2.54 cm.

†These measures were derived by adding popliteal height, sitting elbow height and shoe height. Note that a height-adjustable chair is assumed, with: Chair seat height = Popliteal height + Shoe height.

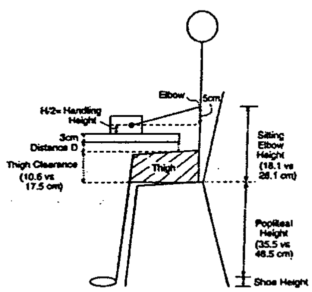
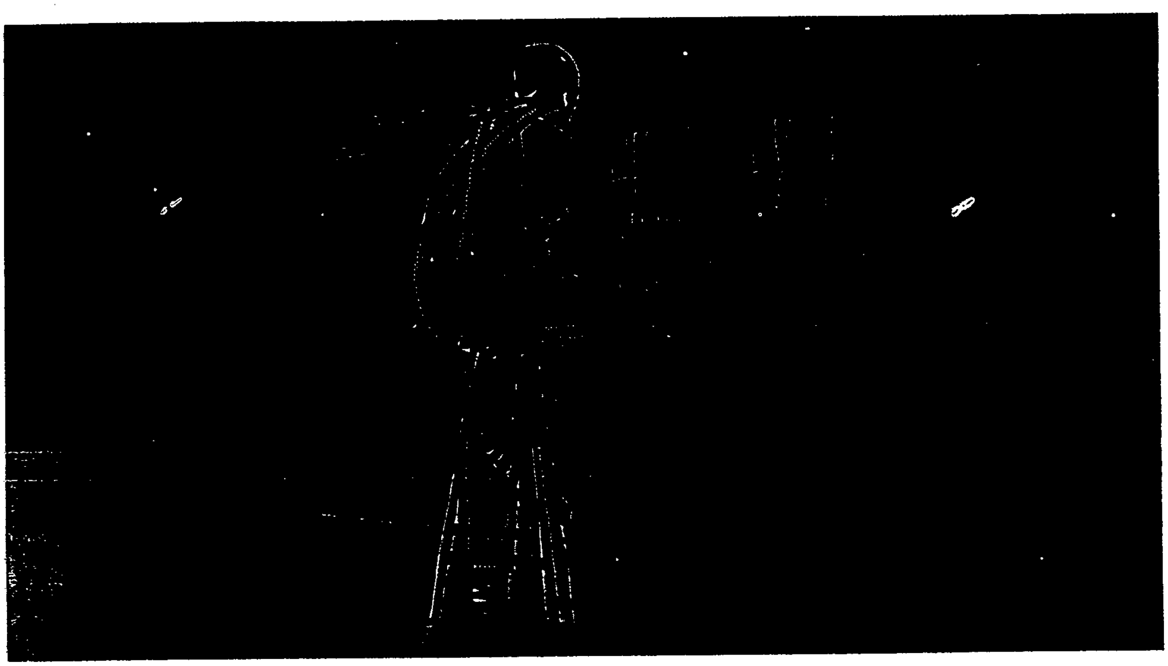


Figure 6.5 Calculation of product height. In the calculations assume that D = 0. The numbers given in parentheses are the 5th and 95th female percentiles

A Guide to the Ergonomics of Manufacturing

Martin Helander



Taylor & Francis
Publishers since 1798

Chapter 1

Introduction

The word *ergonomics* comes from the Greek *ergo* (work) and *nomos* (law). It was used for the first time by Wojciech Jastrzebowski in a Polish newspaper in 1857 (Karwowski, 1991). In the USA, *human factors engineering* or *human factors* have been close synonyms. European 'ergonomics' has its roots in work physiology, biomechanics and workstation design. 'Human factors', on the other hand, has its origin in experimental psychology and the focus is on human performance and systems design (Chapanis, 1971).

Despite the differences between human factors and ergonomics in the type of knowledge and design philosophy, the two approaches are coming closer. This is partly due to the introduction of computers in the workplace. Design of computer workplaces draws from a variety of human factors and ergonomics knowledge (see Table 1.1). We can illustrate the problem as shown in Figure 1.1. Here a human operator is perceiving information on a display. The information is then interpreted and an appropriate action is selected. The action is executed manually as a control input, which in turn effects the information status on the display.

The environment also affects the human operator. Here it would be appropriate to analyse factors that are external to the task and yet have a great effect on performance and job satisfaction, for example:

- Noise and vibration.
- Heat and cold.
- Work–rest cycle.
- Organizational factors.

To effectively solve a problem related to VDT workplaces, an ergonomist must be able to recognize and analyse a variety of problems and suggest design solutions. This leads to our first maxim: *the primary purpose of ergonomics is design.*

Table 1.1 Design problems arising from the introduction of computers in the workplace

Problem	Knowledge required to solve problem
Work posture	Biomechanics
Keying	Biomechanics
Size of screen characters	Perception, vision research
Layout of screen information	Cognitive psychology, cognitive engineering
Designing new system	Systems design and cybernetics
Environmental factors	Noise, heat stress, cold stress

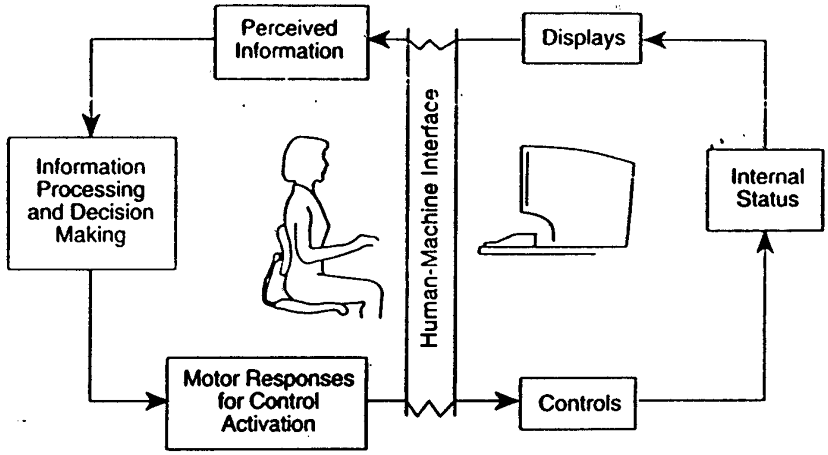


Figure 1.1 Analysis of the human–machine interface requires interdisciplinary knowledge of biomechanics, cognitive psychology and systems design methodology

The existing situation must, therefore, first be analysed, design solutions must be generated and these design solutions must be analysed. The design work can be described using a control loop, as shown in Figure 1.2.

It follows from Figure 1.1 that interdisciplinary knowledge is required: (1) to formulate systems goals; (2) to understand the functional requirements; (3) to design a new system; (4) to analyse the system; and (5) to implement the system. From the feedback loops shown in Figure 1.2 it also follows that design is a never-ending activity. There are always opportunities for improvements or modifications.

A common scenario for the work of an ergonomist could be the following: Imagine that the system shown in Figure 1.1 could be redesigned. Maybe there could be two displays, or perhaps part of the human information processing could be done by a computer, or maybe the manual input to the computer system could be made by computer voice recognition. In the redesign of the system the ergonomist would have to consider many constraints. There will be constraints in allocating tasks (who does what), economic constraints, company constraints, and sometimes labour union constraints. The ergonomist will obtain information from those who use the system or

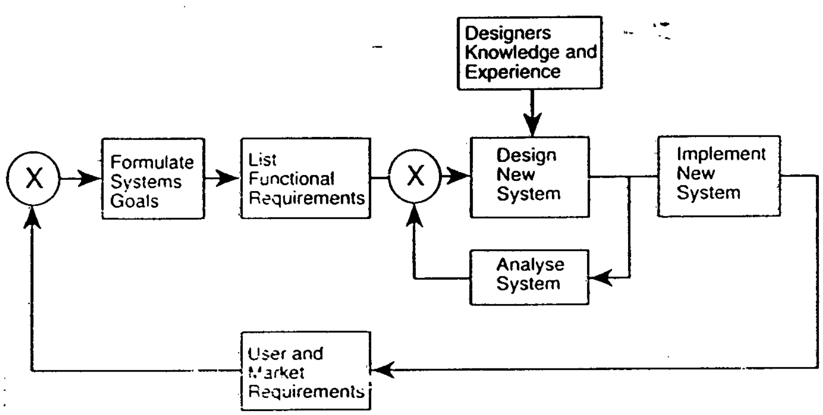


Figure 1.2 Procedure for design and redesign of a system

from another similar system. It will be necessary to consult textbooks and scientific articles, and in the end it may be necessary to evaluate several design options by using rapid prototyping or by performing an experiment with users as test subjects. This scenario leads to our second maxim: *a systematic, interdisciplinary approach is necessary in system design and analysis.*

1.1 Brief History of Ergonomics

In the USA, human factors emerged as a discipline after World War II. There were many problems encountered when using sophisticated war equipment such as aeroplanes, radar and sonar stations, and tanks. Sometimes these problems caused human errors with grave consequences. For example, during the Korean War, more pilots were killed during training than in war activities (Nichols, 1976). This finding focused the interest on the design of controls and displays in aircraft. How could information be better displayed, and how could controls be redesigned and integrated with the task so that they were easier to handle? Many improvements were implemented, such as a pilot's joystick which combined several control functions and made it easier to handle the aeroplane and auxillary combat functions (Wiener and Nagel, 1988). As a result of these improvements and new pilot training programmes, the number of fatalities in pilot training decreased to a fraction (5%) of what they had been previously. Ever since, most of the research in human factors in the USA has been sponsored by the Department of Defense. Consequently, the information available in textbooks on human factors is heavily influenced by military rather than civilian applications of ergonomics.

Some federal agencies have sponsored research on civilian applications: the Federal Highway Administration (design of highways and road signs), NASA (human capabilities and limitations in space, design of space stations), the National Highway Traffic Safety Administration (design of cars, including crash worthiness; effects of drugs and alcohol on driving), the Department of the Interior (ergonomics in underground mining), the National Bureau of Standards (safe design of consumer products), the National Institute of Occupational Safety and Health (ergonomic injuries at work, industrial safety, work stress), the Nuclear Regulatory Commission (design requirements for nuclear power plants), and the Federal Aviation Administration (aviation safety).

In the USA, applications in manufacturing are fairly recent. Eastman-Kodak in Rochester, New York, was probably the first company to implement a substantial programme around 1965. Their approach has been well documented in two excellent books (Eastman Kodak Company, 1983, 1986). At IBM Corporation, interest in manufacturing ergonomics started around 1980. At that time IBM had many human factors experts, but most of them worked on consumer product design. Currently they have turned their interest to computers and software systems. Most of the manufacturing ergonomics has been undertaken by industrial engineers and company nurses. Ergonomics is also discussed in 'quality groups', which comprise a mix of engineers and operators (Helander and Burri, 1994).

In Europe, ergonomics has had a different history. The discipline is particularly well established in the UK, France, Germany, Holland, Italy, and the Scandinavian countries. In the former USSR, just as in the USA, the interest was focused primarily on Department of

Defence activities. There have been few applications on the industrial side, but interest is quickly growing.

In many European countries, labour unions have taken an active interest in promoting ergonomics as being important for safety, health, comfort and convenience. The labour unions are particularly strong in the Scandinavian countries and in Germany, where they can often dictate what type of production equipment is purchased.

One may argue that ergonomics is nothing new. Even during the Stone Age individuals were designing hand tools to fit the user and the task (Drillis, 1963). During the Industrial Revolution there were efforts to apply the concepts of a 'human centred design' to tools such as the spinning-jenny and the spinning-mule. The concern was to allocate interesting tasks to the human operator, but let the machine do repetitive tasks (Rosenbrock, 1983). At the beginning of the 20th century, Frederick Taylor introduced the 'scientific' study of work. This was followed by Frank and Lillian Gilbreth who developed the time-and-motion study and the concept of dividing ordinary jobs into several small micro-elements called 'therbligs' (Konz, 1990). Today there are sometimes objections against Taylorism, which has been seen as a tool for exploiting workers. Nonetheless, these methods are useful for measuring and predicting work activities. The time-and-motion study is a valuable tool if used for the right purpose!

It was not until the 1950s that ergonomics became an independent discipline. In the UK, the Ergonomics Research Society was formed in 1950. In the USA, the Human Factor Society was established in 1957. In 1961 the First Congress of the International Ergonomics Association was held in Stockholm, Sweden (Chapanis, 1990). Today, this umbrella association represents about 20 000 ergonomists in 55 countries.

1.2 The Interdisciplinary Nature of Ergonomics

Ergonomists come from a variety of professional fields. This mixed background is well demonstrated by the membership of professional societies which typically consists of engineers, psychologists, and individuals from the medical profession.

To successfully implement ergonomics in manufacturing design and planning, it is often an advantage to be an engineer. Psychologists, medical doctors and industrial nurses can certainly diagnose many ergonomics problems, but sometimes have an insufficient technical background to suggest how a technical system can be redesigned. Engineers with a background in ergonomics are ideal, as they can analyse different design alternatives for machinery and processes, make trade-offs in the selection of equipment, and arrive at a better solution. Ergonomics is often implemented by work groups where the members have expertise in different areas. Groups composed of workers, engineers, managers and nurses can propose new design solutions. The establishment of such groups is typical of the complex decision-making found in modern manufacturing.

1.3 Ergonomics for Productivity, Safety, Health and Comfort

In many industries ergonomics is implemented primarily as a means of reducing high injury rates and high insurance premiums. In the USA, a worker's compensation premiums often amount to 15% of the salary. This is because there are many back injuries due to materials handling and injuries to the joints in the arms, shoulders and neck due to poor work posture.

During the past 5 years many injuries due to cumulative trauma disorders, carpal tunnel syndrome and tenosynovitis have been reported. At the same time, the number of back injuries remains high, and is still the main cause of industrial injury. It is estimated that the annual cost of musculoskeletal disease in the UK exceeds £25 billion.

The reporting of injuries is affected not only by the actual injury, but also by psychological and sociological factors. A study by Hadler (1989) compared disabling back injuries in France, Switzerland and The Netherlands. He observed that not only were the legislative programmes in the three countries different, but the patterns of reported injuries were also different. The conclusion was that there are several psychological, attitudinal and ethical factors which determine what is reported as an accident or injury and what remains unreported. Individuals will sometimes report particular symptoms because they are 'recognized' by the country's legislation or by society. Different countries might pool injuries under different names. One interesting difference is between VDT operators in the Scandinavian countries and the USA. In the USA there is a prevalence of injuries due to cumulative trauma disorder and tenosynovitis of the hand and of the wrist. These types of injuries are more rare in Scandinavian countries, where operators complain more about pain in the neck and the shoulder. Certainly there must be a connection between the two, but the prevalent ethic of one country is different from that in the other.

While the reduction of injuries and improved health of workers is a very important reason for implementing ergonomics, it is a fairly negative one. Management is forced to implement ergonomic measures to reduce the injury rate. The author is concerned that this 'negative' message will dominate, so that industry leaders will ignore what could be a much more important driving factor for ergonomics, namely increases in productivity. Ergonomic improvements in workstations, industrial processes, and product design can be undertaken from the point of view of productivity, and there can be tremendous gains. Management is often unaware of poor working conditions, and what types of improvement could improve productivity. Workers in plants and in offices usually adapt to the poor conditions – but the cost is increased production time, lower quality of production and, of course, increased injury rate. The two case studies in Chapter 2 illustrate the potential of ergonomics to improve productivity.

Ergonomics is also highly related to industrial safety. If workers can perceive hazards, if there are relevant warning signs, if controls are easy to use, if work postures are acceptable, if noise and other environmental stressors are reduced, if there is collaboration between workers and management based on mutual understandings, and if there is good housekeeping, then safety will improve. Ergonomics measures regarding safety are somewhat different from the conventional, somewhat mechanistic approach often taken in industrial safety. Ergonomics can improve safety through worker's attitudes, perception, decision-making, and risk-taking behaviour.

Figure 1.3 summarizes how an ergonomics systems analysis can be undertaken with at least three different objectives in mind: (1) ergonomics, (2) production, and (3) quality of manufacturing.

In the design of any complex system it becomes necessary to apply

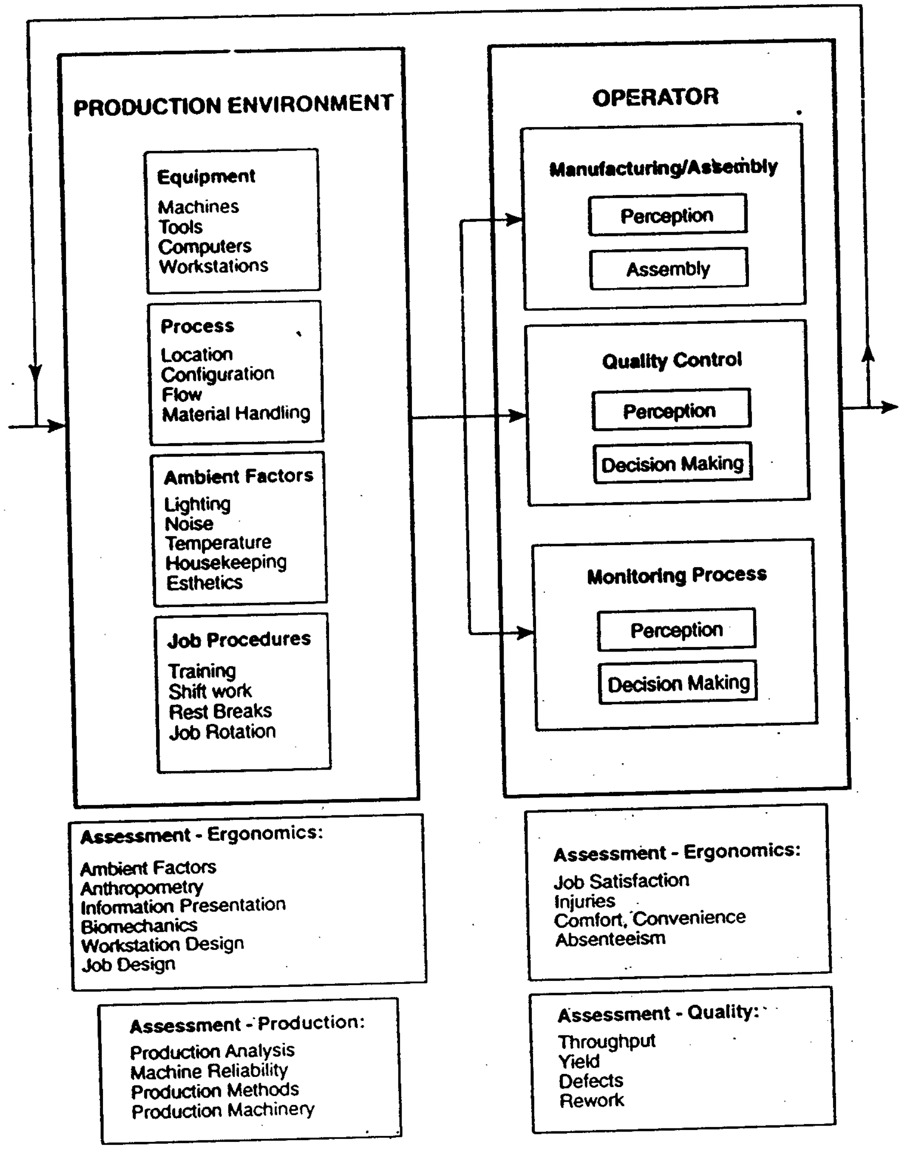


Figure1.3 A production environment / operator system. There are three broad criteria for assessment: ergonomics, production, and quality

many criteria simultaneously. All these criteria must be at least partially satisfied or, to use Simon's (1969) terminology, multiple criteria must be 'satisficed'. In other words, one cannot accept a manufacturing situation where either the production process, ergonomics, or quality of manufacturing are substandard. All assessment criteria must be at a certain minimum level to be acceptable.

The two case studies in Chapter 2 illustrate how ergonomic improvements can be implemented in manufacturing. The ergonomic changes improved all aspects of system performance. There were no (obvious) conflicts between ergonomics and productivity – a win–win situation, as they say.

apter 6

hoice of Work Posture: Standing, itting, or Sit–Standing

Engineers who design production processes take on a great responsibility. In designing products and processes one must consider how the workstation will be laid out and what type of work posture is convenient for the job. Many engineers, however, focus on the engineering aspects and the design for the worker is done as an afterthought, using fairly simplistic methods. In this chapter we propose criteria for when sitting or standing is appropriate. We also provide measures for appropriate work height.

Examples of rk Postures

One conventional engineering solution is the prescription of an 'industrial height' workstation with a 92 cm (36 in.) high work table. This can accommodate both sitting and standing operators. The working height for the standing operator is about 92 cm (36 in.), and a sitting operator can use a high chair with a footrest or a ring support. Such flexibility in a workplace is indeed desirable and Figure 6.1 illustrates how flexibility for sitting or standing can be advantageous for many tasks.

However, sometimes the use of a conventional industrial height workstation creates problems. It is not an appropriate design solution for dedicated seated tasks, which is illustrated by the microscope workstation shown in Figure 6.1(C). Working with a microscope is a seated task. This job requires a very precise and static work posture. There is no reason to consider a standing work posture, and hence a regular table should be used. This has one important side-benefit in that the operator can put his or her feet on the floor, which improves comfort.

Engineers are sometimes short-sighted in their concentration on the technical aspects of the problem. Figure 6.2 illustrated four operators working with very expensive machinery. From these examples it may seem that the greater the technological challenge, the greater is the likelihood that the human element will be forgotten.

Figure 6.2(A) shows an operator working with a scanning microscope. This was a low magnification microscope, with a large exit pupil and it was fairly easy to look through. (High magnification microscopes have a small exit pupil and cannot tolerate any deviation in eye position.) The first obvious problem was that the operator was standing. The second problem was that the scanning microscope moved back and forth while scanning. Therefore the operator had to move back and forth while looking into the microscope – a very demanding task. Due to the bent-over, standing posture, only short operators could perform the task. Rather than having the microscope move, the inspected elements should have moved. Another (less

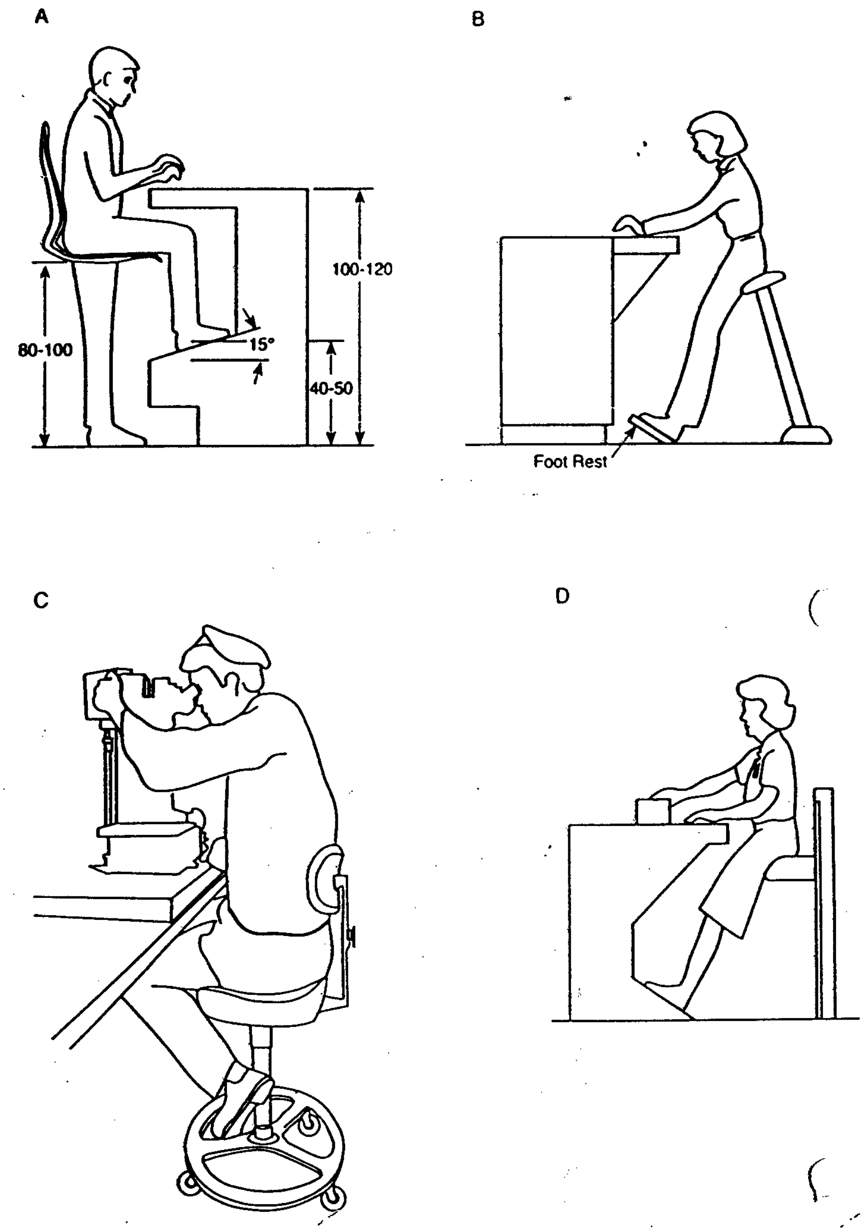


Figure 6.1 (A) A worktable for alternatively sitting and standing – in this case the table at 110–120 cm is higher than the conventional 92 cm (36 in.) table. (B) and (D) Variations of sit-stand arrangements – the operator is free to alternate between standing and sit-standing. (C) Misapplication of a 92 cm (32 in.) industrial height table – working with a microscope is a dedicated seated task, and a regular height table should be used

desirable) solution is to use a moving chair that is synchronized with the microscope movements.

Figure 6.2(B) illustrates a clean-room process which was supposed to be totally automated. However, this very expensive piece of automation never worked out. Visual inspection tasks needed to be performed by a human operator. The main problem was that there was no leg room for the operator sitting at the machine. An armrest was improvised and put on top of the equipment. The operator could then lean sideways on top of the machine to perform the task. This was a very uncomfortable work posture. The design of this piece of

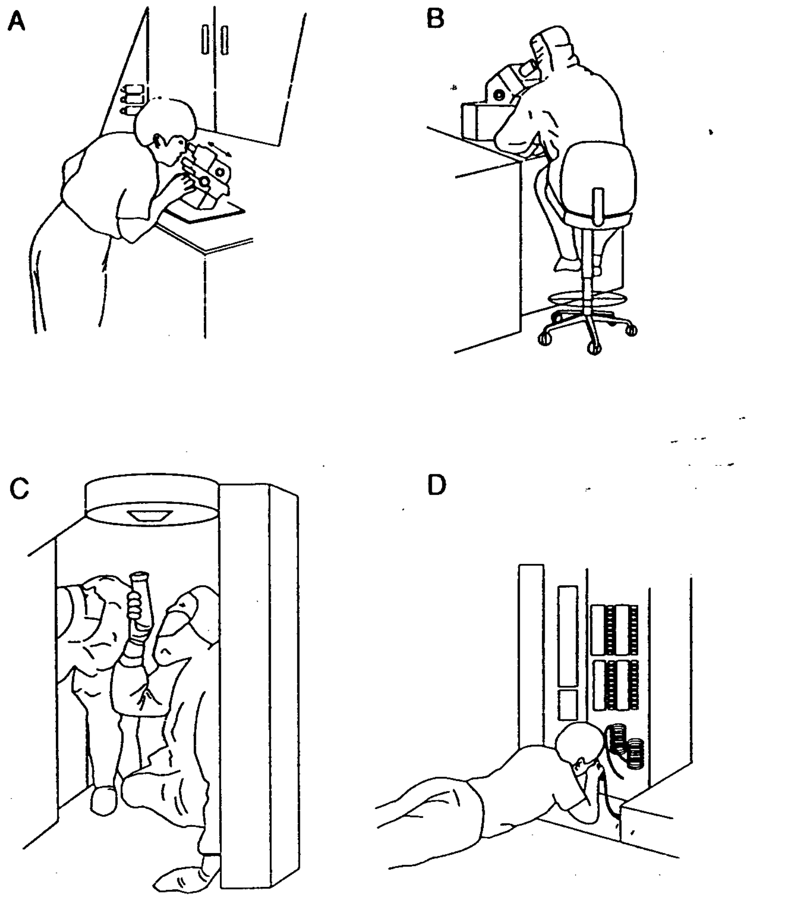


Figure 6.2 (A) The microscope is moving, and unfortunately the operator must move with it. (B) Automated manufacturing equipment - but the automation never worked fully. (C) Routine maintenance with a flashlight. (D) Final assembly of a very expensive piece of equipment

equipment should have made provisions for a manual workstation. Afterwards it became too expensive to rebuild.

Figure 6.2(C) shows two operators in clean-room outfits performing maintenance on process equipment used for manufacturing computer chips. This piece of machinery requires almost constant maintenance, but it was not designed with maintainability in mind (see Chapter 18).

Figure 6.2(D) illustrates an operator lying on the floor completing the final assembly on a piece of electronic equipment which is located inside a steel housing. It was difficult for the operator to reach and to see, and many costly operator errors were reported. As a solution, the company obtained lifting devices to elevate the equipment to a regular working height. The number of operator errors decreased significantly.

It seems inevitable that engineers must expand their responsibilities to consider the consequences of process design for the types of activity that are created. Workstations with ergonomic problems are unproductive, provoke human errors and create costly quality defects. Sometimes the functionality and engineering perfection of a technical system must be compromised to make it more human. Meister (1971) pointed out that engineers are not unwilling to consider the human

operator, but they clearly place a higher priority on engineering problems. This view has to change. A design engineer must bring to the task all the relevant tools and skills to solve problems – technological as well as organizational and individual. Engineering design is a systems problem. Technological solutions can only be considered in conjunction with their environment.

6.2 Identifying Poor Postures

The types of posture that people assume at work can often lead to pain in specific parts of the body. Van Wely (1970) reported that there are certain common complaints for different work postures. Table 6.1 summarizes his observations. This table represents an oversimplification. People usually move around, and it is not easy to characterize a job in terms of a single posture. Nonetheless, the list in Table 6.1 is useful as a checklist for inspections of industrial workstations. For example, if one were to observe an operator who sits with his or her elbows on a high surface, it is a reasonable hypotheses that if the operator has any problems they would be in the upper back or lower neck. If the operator indeed voices such complaints, then our hypothesis has been confirmed, and one would reasonably take measures to improve the work posture by lowering the work height. Similarly, if an operator sits with the head bent back the common complaint is neck pain. If someone is assuming a cramped work posture, without any possibility of moving around, then the muscles involved may hurt.

A joint that is in an extreme position, either fully flexed or fully extended, may develop biomechanical problems. Rather, joints should be at a mid-range position. For example, arms should not be fully extended or flexed. A few examples are given in Figure 6.3.

The recommendations for work posture and the discussions about biomechanical problems are traditional in ergonomics. Yet there are problems that require basic research, as is evident from the following example.

6.2.1 Example: Sitting in India

Professor R. S. Sen from the University of Calcutta in India explained that industrial workers in India often sit hunched directly on the floor without a chair, or they may sometimes sit on a brick (Sen, 1989). They develop motion patterns that can be very different from industrial workers in Western countries. Sometimes they swing their knees back and forth to manipulate items, at the same time as they work with their hands. Although their knees are flexed in an extreme position,

Table 6.1 Work postures and related complaints (Van Wely, 1970)

Posture	Complaint
Standing	Feet, lower back
Sitting without lower back support	Lower back
Sitting without back support	Central back
Sitting without proper foot support	Knees, legs, lower back
Sitting with elbows on a high surface	Upper back, lower neck
Unsupported arms or arms reaching up	Shoulders, upper arms
Head bent back	Neck
Trunk bent forward	Lower back, central back
Cramped position	Muscles involved
Joint in extreme position	Joints involved

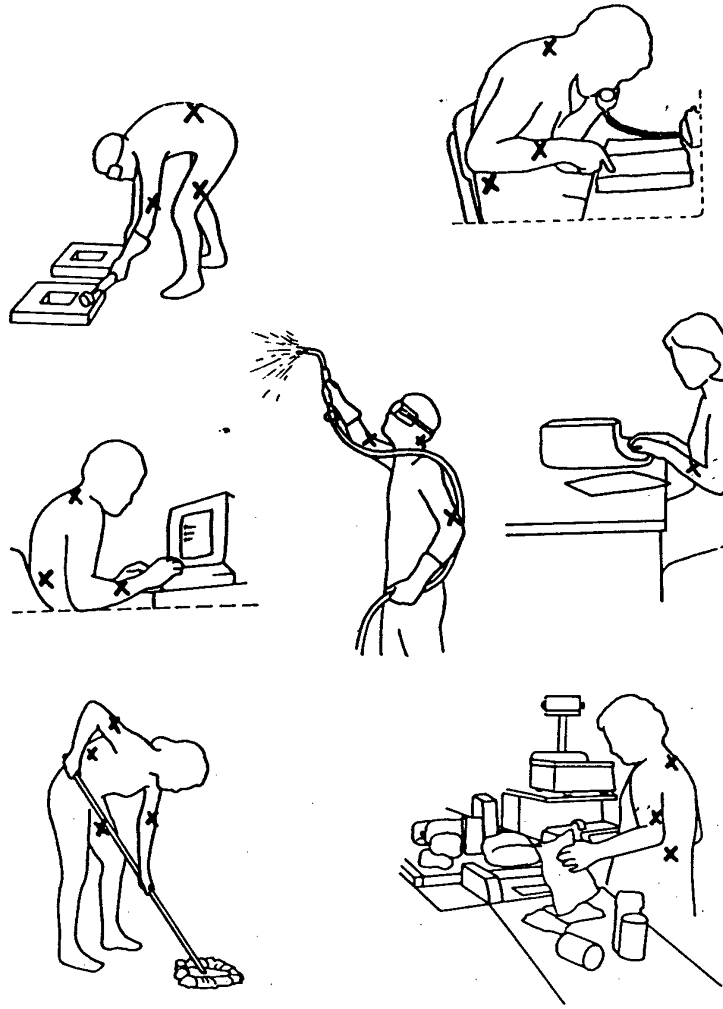


Figure 6.3 Examples of work postures where there are problems with: extreme joint angle, large muscular force, high degree of repetition or high contact pressure (from Webb, 1982)

Professor Sen asserted that these workers do not have any problems with their knee joints. The reason may be that they have been hunch-sitting for their entire lives, and this is a common sitting posture at home or in social gatherings. Professor Sen's statement was surprising, since hunch-sitting violates the principle of keeping the joints in a mid-range position. It seems obvious that more basic research is necessary to analyse this controversy.

6.3 Sitting, Standing or Sit-Standing

We restrict our discussion here to the choice of common work postures. There are additional recommendations in this book, particularly in Chapter 7.

Depending upon the type of task, it may be advantageous for an operator to stand, sit, or sit-stand (Eastman Kodak, 1983; Michel and Helander, 1994).

- If there is frequent handling and lifting of heavy objects it is preferable to stand up. However, sit-standing may be an option (see Table 6.2).

Table 6.2 Preferred work posture for different tasks

Type of task	Preferred work posture: First choice	Second choice
Lifting more than 5 kg (11 lb)	Standing	Sit-standing
Work below elbow height (e.g. packaging or assembly)	Standing	Sit-standing
Extended horizontal reaching	Standing	Sit-standing
Light assembly with repetitive movements	Sitting	Sit-standing
Fine manipulation and precision tasks	Sitting	Sit-standing
Visual inspection and monitoring	Sitting	Sit-standing
Frequent moving around	Sit-standing	Standing

- For packaging, or other tasks where objects must be moved vertically below the elbow height, it is preferable to stand or sit-stand. A sitting posture would not be feasible since the hands are reaching downwards and the table cannot be put at a sufficiently low level without interfering with the operator's legs.
- If the task requires extended reaching it is sometimes preferable to stand or sit-stand, as the operator can then reach further.
- Light assembly with repetitive movements is a common task in industry, and sitting is preferable. A table is necessary to organize part bins, fixtures and incorporate work aides and supports to relieve local body fatigue due to repetitive movements.
- For fine manipulation and precision tasks the operator usually wants to support the underarms. Sitting is definitely preferred.
- Visual inspection and monitoring is best done sitting. The sitting work posture makes it possible to focus one's attention better than if standing.
- If the work task involves a variety of subtasks and also frequent moving around, it may be preferable to sit-stand, since the operator does not then have to get in and out of the chair.

The recommendations in Table 6.2 represent a simplification, since there may be other task characteristics that could influence work posture. The recommendations should therefore be used as a first approximation in understanding what the main options are. As we have discussed elsewhere, a task analysis is helpful in understanding the advantages and disadvantages with various design parameters, and how they trade off.

For most of the tasks in Table 6.2 the sit-standing posture is the second choice. This arrangement has become increasingly common in industry during the last 10 years. Sit-standing is convenient for many tasks, and there are biomechanical advantages since the pressure on the spine and the lower back is about 30% lower for sit-standing (and standing) as compared with sitting (Andersson and Örtengren, 1974).

6.4 Hand Height and Determination of Table Height

There are standard recommendations in the ergonomic literature for table (work surface) height for seated and standing workplaces (Ayoub, 1973; Kroemer *et al.*, 1994). Figure 6.4 illustrates that for a tall product, the work table must be put at a lower height than for a flat product

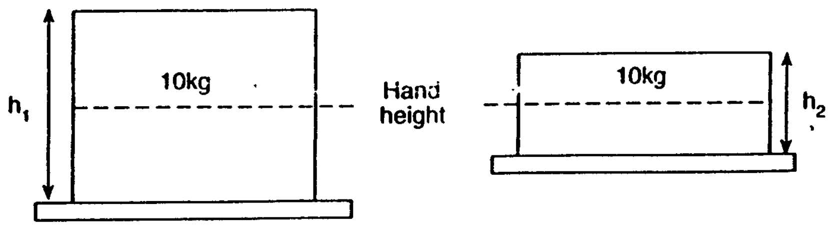


Figure 6.4 The table height is partly determined by the height of the product and the hand height (it is assumed that the products are manipulated or held at the intermediate height)

to arrive at a suitable hand position (Eastman Kodak Co., 1983).

The most advantageous hand position depends on the type of task. For heavy work, it is most convenient to hold the hands about 15 cm (6 in.) below elbow height. The arms and the body can then exercise a greater leverage to perform the heavy task more efficiently. For light assembly work the preferred hand height is about 5 cm (2 in.) below elbow height.

Typing is often performed with the hands about 3 cm (1 in.) above elbow height. For precision work with supported elbows and/or supported underarms, the hand height should be about 8 cm (3 in.) above elbow height. It is easier to perform precision work with the hands and underarms supported. Another reason is that precision work involves small parts and fine details which can be viewed more easily if the objects are closer to the eyes (at about reading distance).

There are individual preferences in work posture. In typing, for example, some individuals may prefer to work with horizontal underarms, but others prefer to raise the keyboard to a higher level. Therefore, the values listed in Table 6.3 are intended as guidelines rather than absolute recommendations. Individuals indeed have different preferences which, combined with anthropometric requirements of a 5th to 95th percentile design, result in a fairly wide range of values. To arrive at suitable values for table height or work bench height from Table 6.3 the handling height of the product must be deducted.

Table 6.3 Measures (cm) of preferred hand height over the floor

		Preferred hand height over floor* (cm)			
		Standing (5th–95th)		Sitting† (5th–95th)	
Type of task	Hand height = Elbow height ±	Male	Female	Male	Female
Heavy lifting	−15 (Range: −20 to −10)	91–110	85–110	Not recommended	
Light assembly	−5 (Range: −10 to 0)	101–120	95–110	59–79	55–73
Typing	+3 (Range: 0 to +6)	109–128	103–118	67–87	63–81
Precision work	+8 (Range: +5 to +10)	Not recommended		72–92	68–91

*The range for females and males are 5th to 95th percentile (see Table 3.2) and were obtained by deducting or adding the value for hand height. Shoe height of 3 cm is included. 1 in. = 2.54 cm.

†These measures were derived by adding popliteal height, sitting elbow height and shoe height. Note that a height-adjustable chair is assumed, with: Chair seat height = Popliteal height + Shoe height.

6.4.1 Example 1

In this industrial task, 25 kg boxes are transported on a conveyor belt. The operator must turn them over to label both sides. The boxes are 50 cm high and are handled at half-height (25 cm). Calculate the preferred height of the conveyor belt using a 5th to 95th percentile range for standing male operators.

Solution: from Table 6.3 the range for hand height over the floor is 91–110 cm. Deducting 25 cm gives a range of 66–85 cm for the height of the conveyor.

6.4.2 Example 2

Calculate the range of adjustability for a typing table for female 5th to male 95th percentile operators.

Solution: the range for hand height is 63–87 cm. Assuming a 3 cm high 'home (centre row) row' of the keyboard, the table top height is 60–84 cm (23.5–33.0 in.).

6.4.3 Example 3

In a manufacturing plant, sitting workstations will be used for light assembly. Assuming a female population of workers, and that the hand is held at elbow height minus 5 cm, the hand height above the floor is 55–73 cm. Assume further that the product has a handling height of *H*/2 cm, where *H* is the product height. What is the maximum product height if the worktable is 3 cm thick?

Solution: the solution to the problem is shown in Figure 6.5:

$$\text{Sitting elbow height} = 5 + \frac{H}{2} + 3 + \text{Thigh clearance (cm)}$$

The 5th percentile female operator has a sitting elbow height of 18.1 cm, which is not enough to accommodate the thigh clearance of 10.6 cm, table thickness of 3 m and a hand height 5 cm below elbow height. In this case $H = -1.0$ cm. Obviously, for small parts assembly this workstation is still acceptable, but if large products are handled

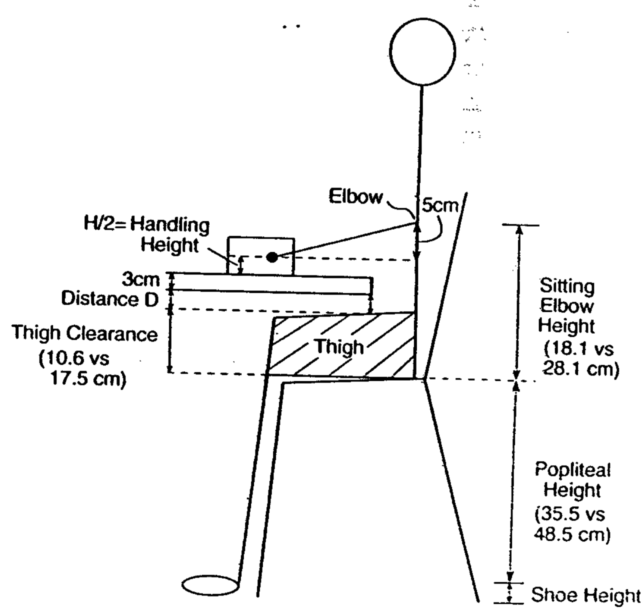


Figure 6.5 Calculation of product height. In the calculations assume that D = 0. The numbers given in parentheses are the 5th and 95th female percentiles

we may want to consider a sit-standing or standing work posture. This does not imply that one would disallow products with greater height at a sitting workstation. Operators can adapt to some extent, for example by gripping the product further down and raising the hands to elbow height. For the 95th percentile female operator, this situation is not so critical because the sitting elbow height is much greater. In this case H = 5.2 cm.

Work at veyors

Conveyors are increasingly used in manufacturing, not only for transportation, but also at assembly lines and for temporary storage, and these systems are often physically connected. At a workstation this arrangement has the advantage that an operator can push items from a moving conveyor to a storage or an assembly line conveyor and is not paced by the line. The operator can thus work faster or slower, as long as the buffer capacity of the storage conveyor is not exceeded (Konz, 1992a).

There is a common belief in industry that the height of the conveyor line must be fixed and consistent throughout a plant. The commonly preferred height is 92 cm (36 in.), which is the same as for industrial standing workstations. This may not always be ideal. Obviously one must avoid downhill and uphill slopes, but there are biomechanical reasons why heights could be different at different locations.

For people working at the conveyors, one should adopt the same rules for determining work height as for regular sitting and standing workstations (see Table 6.3). The purpose is to make the conveyor height convenient for manual work (not for the engineers who design the plant). Thus, the conveyor height should depend on the size of the object that is being handled. For example, if there are large steel drums transported on the conveyor, and if they are handled by workers, then the conveyor height must be very close to the floor to make such handling convenient. Nagamachi and Yamada (1992) demonstrated that the concept of variable conveyor height worked well in a Japanese plant that manufactured air conditioners. The conveyor line was used for assembly and, depending on the height of the work items, the height of the conveyor shifted. They referred to this as a 'Panama Canal Conveyor'. Productivity and quality improved with this design.

If the work along the conveyor is performed sitting, the hand height should be the same as for other sitting workplaces; i.e. for light assembly about 55–79 cm (22–31 in.). There must also be leg room and knee room as for other seated workplaces. In addition, to avoid a bad work posture, the conveyor must be thin so that it can fit in the space between the thighs and underarms. A thick conveyor or a tall fixture will force the operator to raise his or her arms, thereby creating a bad work posture.

Sometimes products on a conveyor line create jams. In order to break up the jams, the conveyor must be accessible from both sides so that two people can work together (Eastman Kodak Co., 1983).

Since conveyor lines can extend throughout an entire plant, it is important to provide crossing points or gates where people and material can be brought through. It should not be necessary to crawl under the conveyor line.

Conveyors can help in manual materials handling at workstations. It should be possible to slide assemblies along the conveyor rather than to lift them. This can be achieved by using special rollers or low

friction material which are used to connect a moving and a stationary conveyor at a workstation.

Loading, and especially the unloading, of conveyors present hazards and can result in overexertion and back injuries. Typically unloading is much more demanding and there are three times as many injuries as for loading. This is because the operation is often paced by the movement of the conveyor line, and products typically weigh more when they come off the conveyor line after the assembly (Cohen, 1979).

People working at conveyor belts may develop 'conveyor sickness' (T. G., and R. L., 1975). This may be true not only for moving conveyors but also for other moving objects such as carousel storage units. It seems that if the conveyor speed is greater than 10 m/min (32 ft/min) operators can develop nausea and dizziness. This may be particularly common if a person sits sideways to the conveyor, so that the motion is perceived with the peripheral vision.

Principles & Practice of Anthropometry

Ravindra Goonetilleke, Ph.D.
Dept. of Industrial Engineering & Engineering Management
Hong Kong University of Science & Technology

Contents

- What is Anthropometry?
- Measurement methods
- Terminology
- Basic statistics and assumptions
- Errors
- Sample size determination

Anthropometry

"Science of human measurement and the art of application that establishes the physical geometry, mass properties, and strength capabilities of the human body"

Roebuck

Anthropometry

Anthropos = human

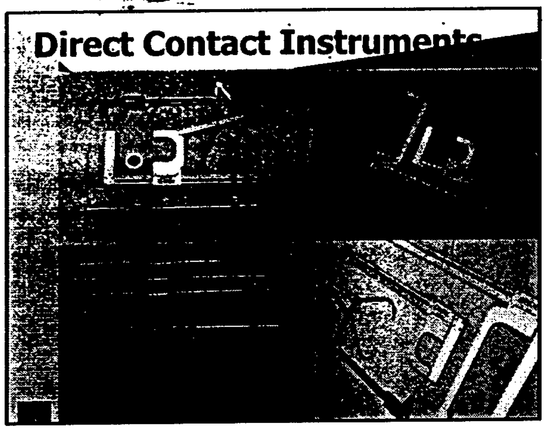
metrikos = relates to measuring

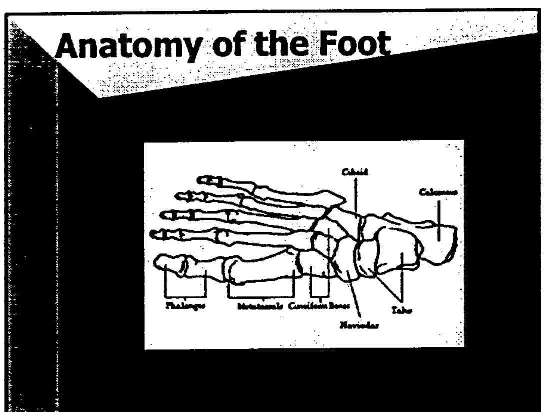
Measurement

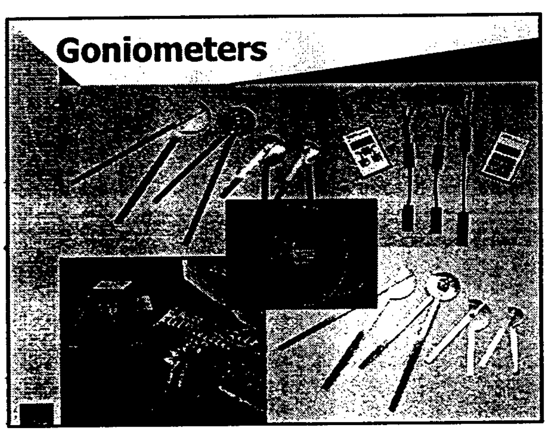
- Why?
- What?
- Who?
- How?

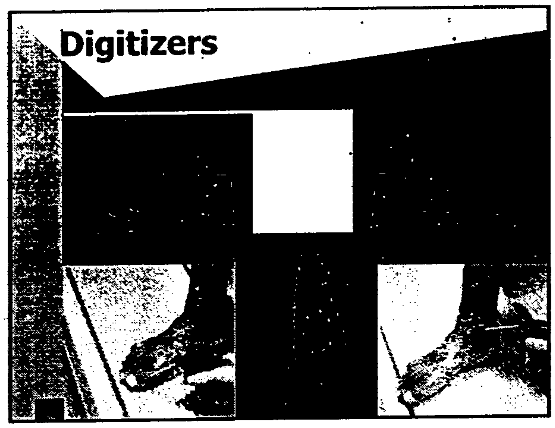
Measurement Methods

- Direct contact
  - Anthropometer
  - Calipers
  - Flexible steel tape
  - Stadiometer
  - Goniometers
  - Digitizers
- Indirect (remote)
  - Photography & video imaging
  - Stereo photography
  - Optical scans
  - Structured lighting systems
  - Internal imaging


Direct Contact Instruments


Anatomy of the Foot
Cuboid
Calcaneus
Phalanges
Metatarsals
Cuneiform Bones
Navicular
Talus


Goniometers



Differences among types

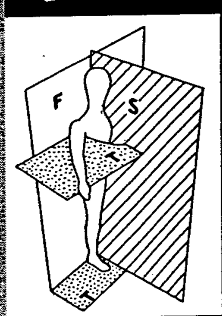
- Cost
- Time
- Accuracy
- Precision

Standardize Procedures?

- Allows comparisons between studies
- Allows comparisons over time

TERMINOLOGY

Measuring Planes



Anatomical Landmarks

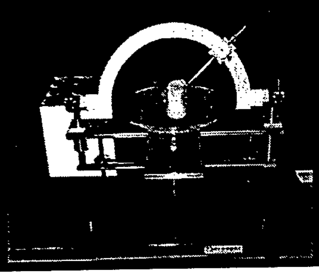
- Medical
- Anthropological

See printed sheet

Landmarking

- Locate site on the surface
- Skeletal landmarks will require palpation
- Sites marked on the surface of the skin

Example Device



What side to measure?

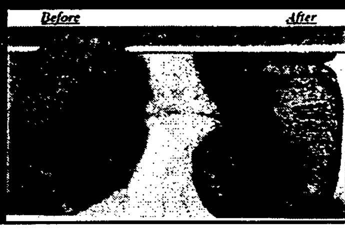
- Differences exist between left and right sides
- Statistic to use

  $= \dfrac{\text{difference between sides}}{\text{standard deviation}}$

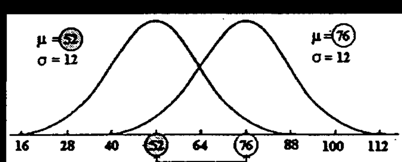
  0.20 (small effect)
  0.5 (medium effect)
  0.80 (large)

What time to measure?

- Variations throughout the day
- Variations with activity



Human Variability



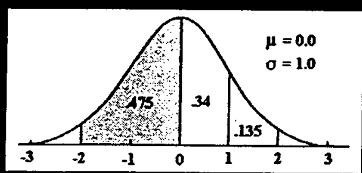
Normal Distribution

Probability Density Function (pdf)

$$f(x) = \frac{1}{\sigma(\sqrt{2\pi})} \{e \quad \}$$

mean = μ = tells where distribution is located on horizontal axis.
standard deviation = σ = index of variability in the population

Area Under Normal Cu



Characteristics of Curve

- 50% of the population is less than the average
- 50% of the population is more than the average

Mean = 50th percentile (% ile)

Percentiles

standard normal deviate $z = \frac{(X-\mu)}{\sigma}$

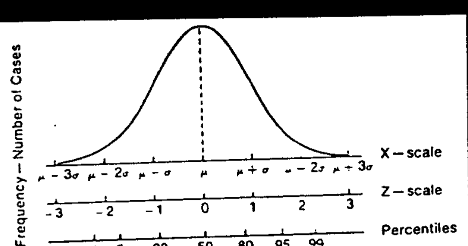
pth percentile $X(p) = \mu + z\sigma$

Percentile	Z
2.5th	-1.96
5th	-1.64
50th	0
95th	1.64
97.5th	1.96

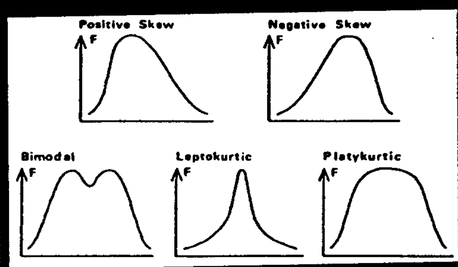
Percentiles

- A value such that at least p% of the items in the data set are less then or equal to its value and at least (100 - p)% of the items are greater than or equal to it
- Example: the *60th percentile* means that 60% of values in the data set are less than or equal to it and (100 - 60) 40% are greater than or equal to it.

Transformations



Deviations from Normality



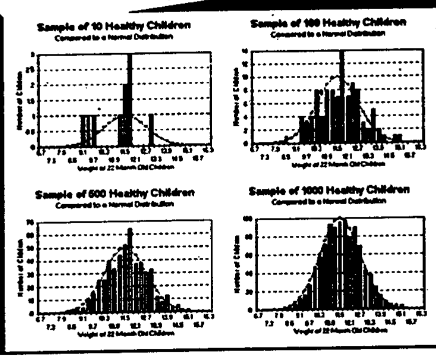
Testing for Normality

- Is mean = median? (quick and dirty)
- Lilliefors test (1960)
- Kolmogorov-Smirnoff test on cumulative distribution
- Shapiro-Wilks W test
- Stem and leaf plots
- Cox test for skewness and kurtosis

Non-Normality

- Errors will accrue and the magnitude determined by the deviation from normality.
- Errors in many cases negligible.

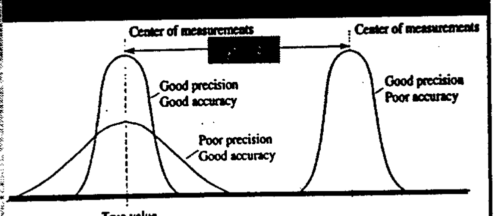
Sample Size



Threats

- Accuracy - The extent to which a measured value corresponds to the "true" value. (Absence of BIAS)
- Precision - Variability in repeated measures taken on the same subject over time. (DISPERSION)
- Validity - the extent to which a measurement actually measures some characteristic

Accuracy & Precision



Bias

- Instrument calibration is an effective means to minimize, but not totally eliminate bias.
- If bias is small relative to the magnitude of the measurement, it is acceptable.

Precision

Three primary sources:

- Failure of the instrument to exactly repeat itself
- Failure of an operator to exactly reproduce the measurement method.
- Variations in the person being measured (due to physiological variations) - generally neglected.

Technical Error of Measurement

- Obtained by repeating measurements on the same subject, either by the same observer, or by two or more observers.

Purpose of TEM

- Compare (using F-test) TEM of measurer and well-trained anthropometrist
- If no significant differences, then the measurer can be considered to be eligible for the job.

TEM

$$TEM^2 = \frac{\sum D_i^2}{2N}$$

D_i = difference between two measurements for the i^{th} subject

N = number of individuals measured

Total TEM

$$= \sqrt{[TEM(intra)^2 + TEM(inter)^2]}$$

TEM (for more than 2 measurements per subject)

$$TEM^2 = \frac{\sum_{i=1}^{N} \left[\sum_{j=1}^{K} x_j^2 - \frac{(\sum x_j)^2}{K} \right]_i}{N(K-1)}$$

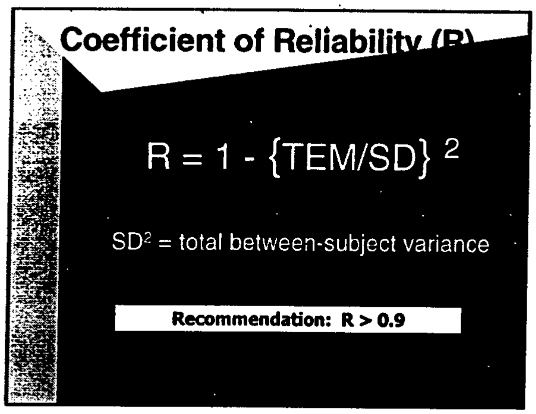
x_j^2 = squared value of the jth replicate (j= 1,2, ...K)
K = number of determinations of the variable taken for each subject
N = number of subjects (i= 1,2, ...N)

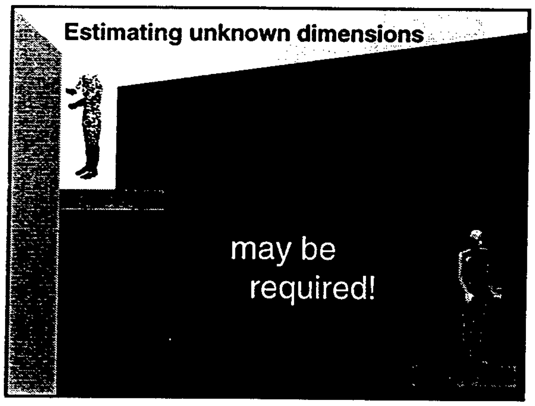
Acceptable TEM?

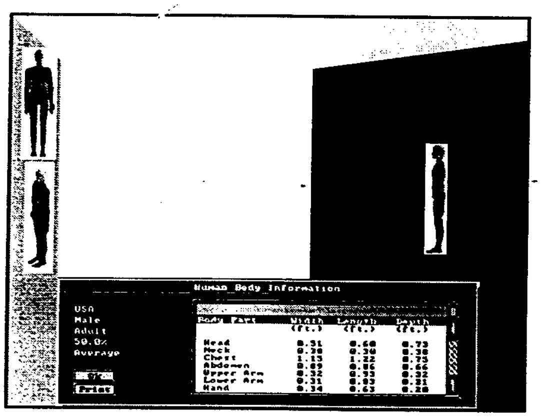
- If intra- and inter- (with more than one measurer) observer TEM come close to a reference value in a series of repeated measurements, then the measurement can be considered accurate.

Reference Values

Measurement	Intra-examiner TEM	Inter-examiner TEM
Sitting height (cm)	0.535	0.705
Biacromial Breadth (cm)	0.544	0.915
Bitrochanteric breadth (cm)	0.523	0.836
Elbow breadth (cm)	0.117	0.154


Coefficient of Reliability (R)
R = 1 - {TEM/SD} 2
SD2 = total between-subject variance
Recommendation: R > 0.9


Estimating unknown dimensions
may be required!


Human Body Information
USA
Male
Adult
50.0%
Average
Print
Body Part Width (ft.) Length (ft.) Depth (ft.)
Head 0.31 0.60 0.73
Neck 0.30 0.30 0.38
Chest 1.15 1.22 0.75
Abdomen 0.89 0.86 0.66
Upper Arm 0.32 0.93 0.32
Lower Arm 0.31 0.83 0.21
Hand 0.34 0.63 0.20

Sum of Dimensions

If p= (x+y)

$$m_p = m_{(x+y)} = m_x + m_y$$

$$s^2_{(x+y)} = s^2_x + s^2_y + 2rs_x\, s_y$$

r = sample correlation coefficient

Difference

If p= (x-y)

$$m_p = m_{(x-y)} = m_x - m_y$$

$$s^2_{(x+y)} = s^2_x + s^2_y - 2rs_x\, s_y$$

r = sample correlation coefficient

Ratio Scaling

m_y / m_x (in population a) ~ m_y / m_x (in population b)

s_y / s_x (in population a) ~ s_y / s_x (in population b)

Human Diversity

- Gender
- Ethnic
- Age
- Social class & occupation

What are the implications?

Whole-Body Density

- The average density function of body build is called somatotype
  - Mesomorphic (relatively predominant muscular tissue and heavy bones)
  - Endomorphic - (relatively large amounts of soft fatty tissue, a large belly)
  - Ectomorphic (relatively little fat or muscle - small bones and thin chest)

Ponderal Index $c = h/w^{1/3}$

Terminology: Anatomical Landmarks

Medical Measuring Points

I.

A Acromion (lateral margin)
B Greater tuberosity (most lateral part)
C Lateral (radial) epicondyle of humerus (most prominent lateral part)
D Styloid process of radius (tip)
E Anterior superior iliac spine
F Greater trochanter (most lateral part)
G Medial (tibial) epicondyle
H Medial malleolus (tip)

X1-4 Construction Access of Upper Extremity

X1 Head of humerus
X2 Capitulum humeri
X3 Capitulum radii
X4 Ulnar styloid process

Y1-4 Weightbearing Lines of Lower Extremity

Y1 Ilium
Y2 Femoral head
Y3 Knee (patella)
Y4 Ankle (talus)

a Acromion
i Tip of middle finger
m Ischial tuberosity
s Symphysis pubis
t Sternal notch
u Sternoclavicular joint
v Tip of second toe
w Tip of thumb
x Xiphoid process

II.

1 Acromion
2 Radial (lateral) epicondyle
3 Radial head (uppermost margin)
4 Styloid process of radius
5 Tip of middle finger
6 Iliac crest (most cranial part)
7 Anterior superior iliac spine
8 Greater trochanter (cranial tip)
9 Tibial (medial) condyle (upper margin)
10 Tuber of os calcis (most posterior part)
11 Medial malleolus (tip)
12 Tip of big toe

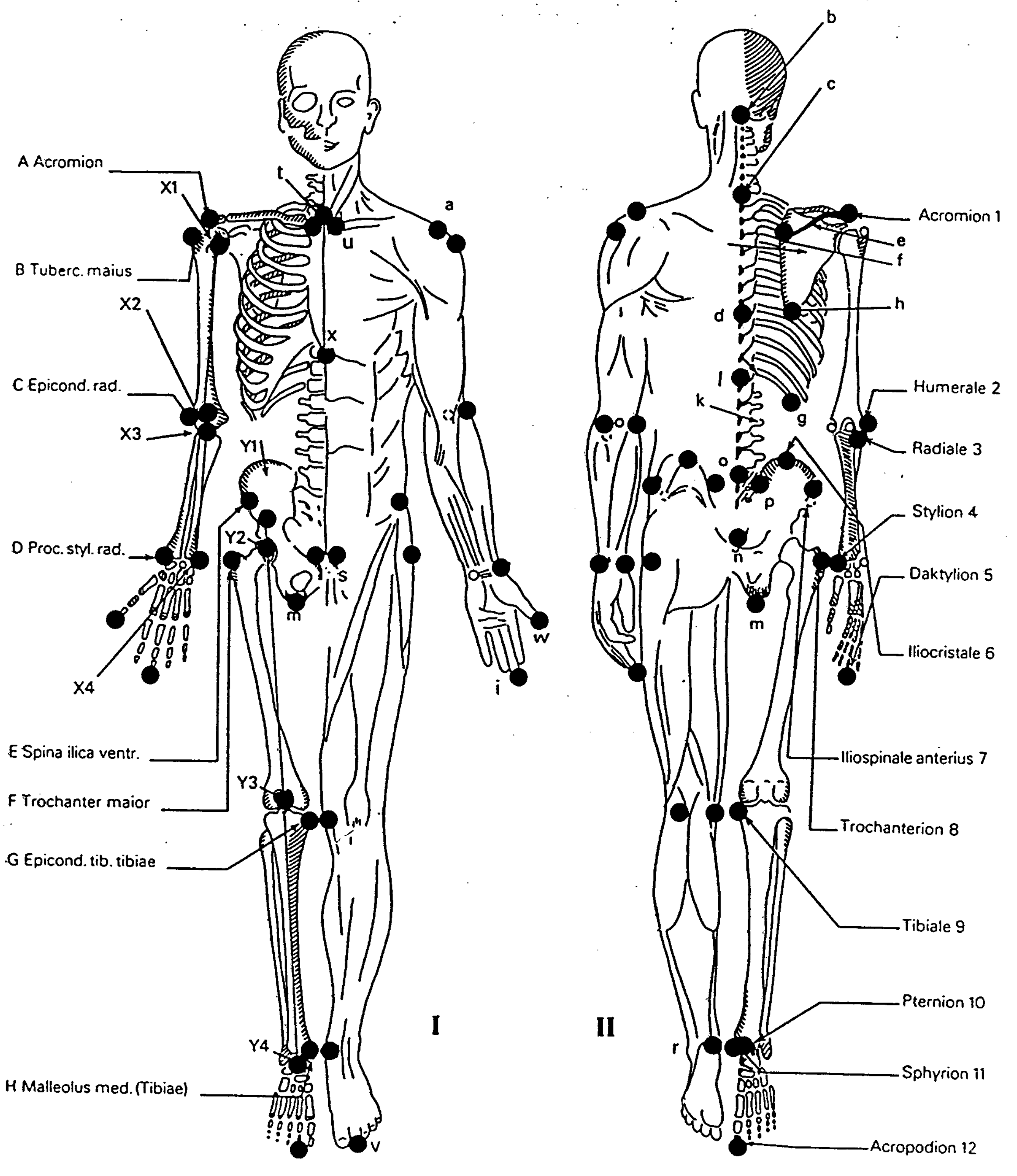
b Occipital protuberance
c Spinal process of C7 (vertebra prominens)
d Spinal process T8
e Spine of scapula
f Root of spine of scapula
g 12th rib
h Inferior angle of scapula
k Transverse process of 3rd lumbar vertebra
l Spinal process of T12
m Ischial tuberosity
n Sacrococcygeal joint
o Lumbosacral junction
p Posterior superior iliac spine
r Tuber calcanei

Anthropological Measuring Points

Anthropological measuring points are more exact than medical measuring points, but are more difficult to obtain and require use of an anthropometer.

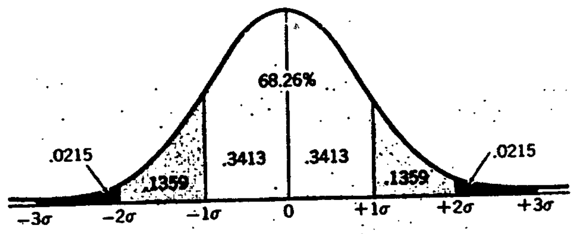
Medical Measuring Points

Main Anthropological Measuring Points



Dark areas on skeleton are visible or palpable under the skin

Measuring points and construction lines redrawn from Lanz, Wachsmuth, Pratische Anatomie, Arm, Bein und Statik, Berlin, Springer Verlag, 1935, 1938.



Different proportions of area under the normal curve within the limits of the various 1σ units on the base line

Let's calculate the 90th %ile of stature for the adult male population.
Assume mean stature = 1680mm standard deviation = 58mm (Hong Kong Chinese, 50%ile man)

From Table 1, we see that for p =90, z=1.28.
90th %ile value for stature = 1680 +58 x1.28 = 1754 mm

Table 1. *p* and *z* values of the normal distribution.
(Source: Bodyspace, Table 2.1, p. 15)

p	*z*	*p*	*z*	*p*	*z*	*p*	*z*
1	-2.33	26	-0.64	51	0.03	76	0.71
2	-2.05	27	-0.61	52	0.05	77	0.74
3	-1.88	28	-0.58	53	0.08	78	0.77
4	-1.75	29	-.055	54	0.10	79	0.81
5	-1.64	30	-0.52	55	0.13	80	0.84
6	-1.55	31	-0.50	56	0.15	81	0.88
7	-1.48	32	-0.47	57	0.18	82	0.92
8	-1.41	33	-0.44	58	0.20	83	0.95
9	-1.34	34	-0.41	59	0.23	84	0.99
10	-1.28	35	-0.39	60	0.25	85	1.04
11	-1.23	36	-0.36	61	0.28	86	1.08
12	-1.18	37	-0.33	62	0.31	87	1.13
13	-1.13	38	-0.31	63	0.33	88	1.18
14	-1.08	39	-0.28	64	0.36	89	1.23
15	-1.04	40	-0.25	65	0.39	90	1.28
16	-0.99	41	-0.23	66	0.41	91	1.34
17	-0.95	42	-0.20	67	0.44	92	1.41
18	-0.92	43	-0.18	68	0.47	93	1.48
19	-0.88	44	-0.15	69	0.50	94	1.55
20	-0.84	45	-0.13	70	0.52	95	1.64
21	-0.81	46	-0.10	71	0.55	96	1.75
22	-0.77	47	-0.08	72	0.58	97	1.88
23	-0.74	48	-0.05	73	0.61	98	2.05
24	-0.71	49	-0.03	74	0.64	99	2.33
25	-0.67	50	0	75	0.67		

p	*z*
2.5	-1.96
0.5	-2.58
0.1	-3.09
0.01	-3.72
0.001	-4.26

p	*z*
97.5	1.96
99.5	2.58
99.9	3.09
99.99	3.72
99.999	4.26

STATIC ANTHROPOMETRIC DATA (SOURCE: BODYSPACE)

- **Standard Anthropometric Postures**

1. Standard standing posture

The subject stands erect pulling himself up to his full height and looking straight ahead, with his shoulders relaxed and his arms hanging loosely by his sides.

2. Standard sitting posture

The subject sits erect on a horizontal surface, pulled up to his full height, looking straight ahead. The shoulders are relaxed, with the upper arm hanging vertically and the forearm horizontal (i.e., elbows are flexed at right angles). The height of the seat is adjusted (or supports placed beneath the feet) until the thighs are horizontal and the lower legs vertical (i.e., knees and ankles are flexed at right angle). Measurements are made perpendicular to two reference planes. The horizontal reference plane is that of the seat surface; the vertical reference plane is a real or imaginary plane which touches the back of the uncompressed buttocks and shoulder blades of the subject. The seat reference point (SRP) lies at the intersection of the vertical reference plane, the horizontal reference plane and the median plane of the body (i.e., the plane which divides it equally into its right and left halves).

- **Common Dimensions**

NOTES: Add shoe correction as necessary for the selected population

1. Stature

Definition: The vertical distance from the floor to the vertex (i.e., the crown of the head).

Applications: As a cross-referencing dimension for comparing populations and estimating data Defines the vertical clearance required in the standing workspace; minimal acceptable height of overhead obstructions such as lintels, roofbeams, light fittings, etc.

A few design applications call for supine or prone body length (in which the subject lies on his back or front, respectively). Such a position lengthens the adult body by approximately 15 mm.

2. Eye height

Definition: Vertical distance from the floor to the inner canthus (corner) of the eye.

Applications: Centre of the visual field; reference datum for location of visual displays; 'reach' dimension for sight lines, defining maximal acceptable height of visual obstructions; optical sighting devices for prolonged use should be adjustable for the range of users.

3. Shoulder height

Definition: Vertical distance from the floor to the acromion (i.e., the bony tip of the shoulder).

Applications: The approximate centre of rotation of the upper limb and, hence, of use in determining zones of comfortable reach; reference datum for location of fixtures, fittings, controls, etc.

4. Elbow height

Definition: Vertical distance from the floor to the radiale. (The radiale is the bony landmark formed by the upper end of the radius bone which is palpable on the outer surface of the elbow.)

Applications: An important reference datum for the determination of work-surface heights, etc.

Note: Some surveys measure to the underside of the elbow when it is flexed to a right angle. This gives a value approximately 15 mm less than the standard measurement.

5. Hip height

Definition: Vertical distance from the floor to the greater trochanter (a bony prominence at the upper end of the thigh bone, palpable on the lateral surface of the hip).

Applications: Centre of rotation of the hip joint, hence the functional length of the lower limb.

6. Knuckle height

Definition: Vertical distance from the floor to metacarpal III (i.e., the knuckle of the middle finger).

Applications: Reference level for handgrips; for support (handrails, etc.) approximately 100 mm above knuckle height is desirable. Handgrips on portable objects should be at less than knuckle height. Optimal height for exertion of lifting force.

7. Fingertip height

Definition: Vertical distance from the floor to the dactylion (i.e., the tip of the middle finger).

Applications: Lowest acceptable level for finger-operated controls.

8. Sitting height

Definition: Vertical distance from the sitting surface to the vertex (i.e., the crown of the head).

Applications: Clearance required between seat and overhead obstacles.

Corrections: 10 mm for heavy outdoor clothing beneath the buttocks; variable amount for seat compression; 25 mm for a hat; 35 mm for a safety helmet.

9. Sitting eye height

Definition: Vertical distance from the sitting surface to the inner canthus (corner) of the eye.

Applications: See dimension 2.

Corrections: 10 mm for heavy outdoor clothing; up to 40 mm reduction for 'sitting slump'; seat compression.

10. Sitting shoulder height

Definition: Vertical distance from the seat surface to the acromion (i.e., the bony point of the shoulder).

Applications: Approximate centre of rotation of the upper limb.

Correction: As for dimension 9.

11. Sitting elbow height (also known as elbow rest height)

Definition: Vertical distance from the seat surface to the underside of the elbow.

Applications: Height of armrests; important reference datum for the heights of desk tops, keyboards, etc., with respect to the seat.

12. Thigh thickness (also known as thigh clearance)

Definition: Vertical distance from the seat surface to the top of the uncompressed soft tissue of the thigh at its thickest point, generally where it meets the abdomen.

Applications: Clearance required between the seat and the underside of tables or other obstacles.

Correction: 35 mm for heavy outdoor clothing.

13. Buttock-knee length

Definition: Horizontal distance from the back of the uncompressed buttock to the front of the kneecap.

Applications: Clearance between seat back and obstacles in front of the knee.

Correction: 20 mm for heavy outdoor clothing.

14. Buttock - popliteal length

Definition: Horizontal distance from the back of the uncompressed buttocks to the popliteal angle, at the back of the knee, where the back of the lower legs meet the underside of the thigh.

Applications: Reach dimension, defines maximum acceptable seat depth.

15. Knee height

Definition: Vertical distance from the floor to the upper surface of the knee (usually measured to the quadriceps muscle rather than the kneecap).

Applications: Clearance required beneath the underside of tables, etc.

16. Popliteal height

Definition: Vertical distance from the floor to the popliteal angle at the underside of the knee where the tendon of the biceps femoris muscle inserts into the lower leg.

Applications: Reach dimension defining the maximum acceptable height of a seat.

17. Shoulder breadth (bideltoid)

Definition: Maximum horizontal breadth across the shoulders, measured to the protrusions of the deltoid muscles.

Applications: Clearance at shoulder level.

Corrections: 10 mm for indoor clothing; 40 mm for heavy outdoor clothing.

18. Shoulder breadth (biacromial)

Definition: Horizontal distance across the shoulders measured between the acromia (bony points).

Applications: Lateral separation of the centres of rotation of the upper limb.

19. Hip breadth

Definition: Maximum horizontal distance across the hips in the sitting position.

Applications: Clearance at seat level; the width of a seat should be not much less than this.

Corrections: 10 mm for light clothing; 25 mm for medium clothing; 50 mm for heavy outdoor clothing.

Note: This is a dimension with a substantial soft tissue component. In studies of physique, etc., the bony dimension bicristal breadth is generally used (measured between the lateral edges of the crests of the hip bones).

20. Chest (bust) depth

Definition: Maximum horizontal distance from the vertical reference plane to the front of the chest in men or breast in women

Applications: Clearance between seat backs and obstructions.

Corrections: Up to 40 mm for outdoor clothing.

21. Abdominal depth

Definition: Maximum horizontal distance from the vertical reference position.

Applications: Clearance between seat back and obstructions.

Corrections: Up to 40 mm for outdoor clothing.

22. Shoulder-elbow length

Definition: Distance from the acromion to the underside of the elbow in a standard sitting position.

23. Elbow-fingertip length

Definition: Distance from the back of the elbow to the tip of the middle finger in a standard sitting position.

Applications: Forearm reach; used in defining normal working area.

Corrections: For general reach corrections see dimension 34.

24. Upper limb length

Definition: Distance from the acromion to the fingertip with the elbow and wrist straight (extended).

25. Should-grip length

Definition: Distance from the acromion to the centre of an object gripped in the hand, with the elbow and wrist straight.

Applications: Functional length of upper limb; used in defining zone of convenient reach.

Corrections: Reach corrections as in dimension 34.

26. Head length

Definition: Distance between the glabella (the most anterior point on the forehead between the brow ridges) and the occiput (back of the head) in the midline.

Applications: Reference datum for location of eyes, approximately 20 mm behind glabella.

27. Head breadth

Definition: Maximum breadth of the head above the level of the ears.

Applications: Clearance.

Corrections: Add 35 mm for clearance across the ears; up to 90 mm for protective helmets.

28. Hand length

Definition: Distance from the crease of the wrist to the tip of the middle finger with the hand held straight and stiff.

Applications: See dimension 34.

29. Hand breadth

Definition: Maximum breadth across the palm of the hand (at the distal ends of the metacarpal bones).

Applications: Clearance required for hand access, e.g., grips, handles, etc.

Corrections: As much as 25 mm for some protective gloves.

30. Foot length

Definition: Distance, parallel to the long axis of the foot, from the back of the heel to the tip of the longest toe.

Applications: Clearance for foot, design of pedals.

Corrections: In many respects surveys of shoes would be more relevant than surveys of feet since their sizes and shapes are often unrelated. For the purposes of argument we could add 30 mm for men's street shoes and 40 mm for protective boots.

31. Foot breadth

Definition: Maximum horizontal breadth, wherever found, across the foot perpendicular to the long axis.

Applications: Clearance for foot, spacing of pedals, etc.

Corrections: See dimension 30; add 10 mm for men's street shoes; 30 mm for heavy boots.

32. Span

Definition: The maximum horizontal distance between the fingertips when both arms are stretched out sideways.

Applications: Lateral reach.

Corrections: See dimension 34.

33. Elbow span

Definition: Distance between the tips of the elbows when both upper limbs are stretched out sideways and the elbows are fully flexed so that the fingertips touch the chest.

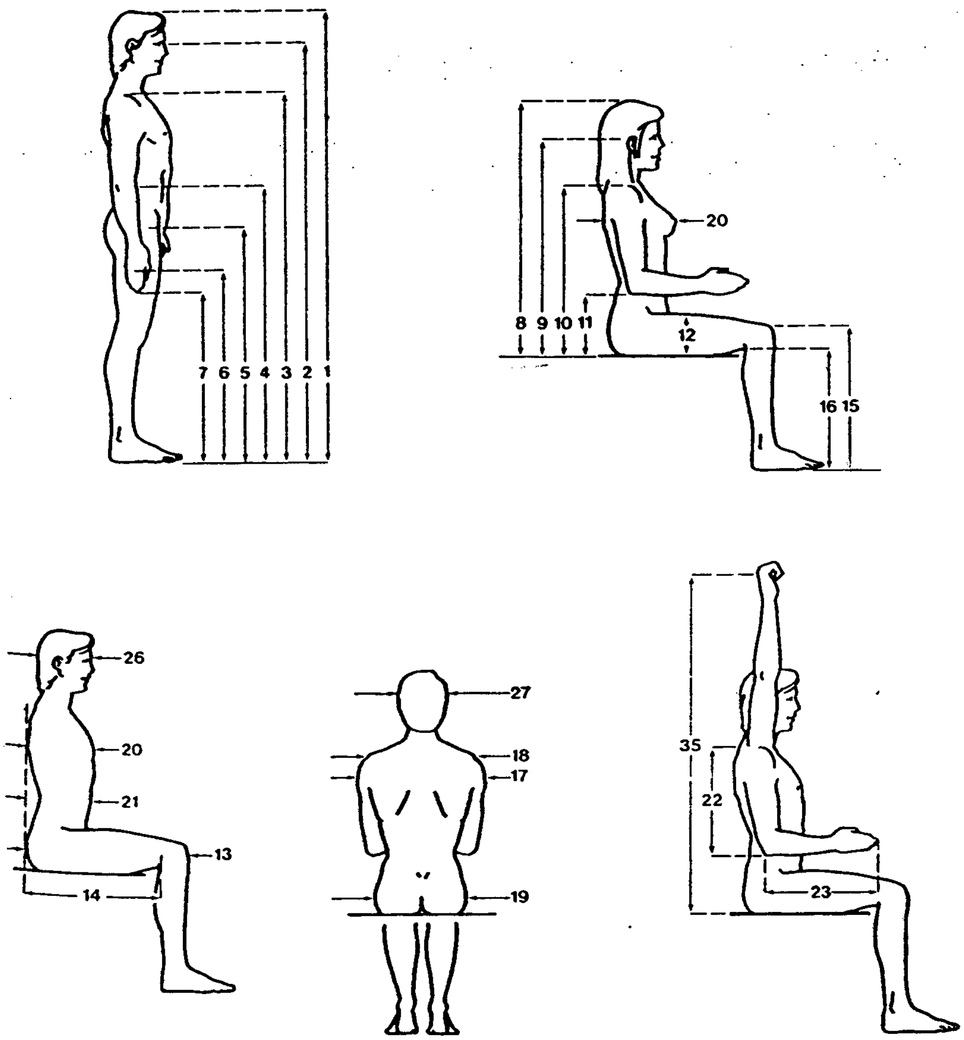
Applications: A useful guideline when considering 'elbow room' in the work-space.

34-36. Grip reaches

Definition: In each case the measurement is made to the centre of a cylindrical rod fully grasped in the palm of the hand. In dimensions 34 and 35 the arm is raised vertically above the head and the measurement is made from the floor or seat surface, respectively. In dimension 36 the arm is raised horizontally forward at shoulder level and the measurement is taken from the back of the shoulder blades. In each case these are 'easy' reaches made without excessive stretch.

Corrections: Some surveys measure reach to the tip of the outstretched middle finger or to the tip of the thumb when it forms a 'pinch' with the index finger. Approximately,

fingertip reach = grip reach + 60% hand length
thumbtip reach = grip reach + 20% hand length


7 6 5 4 3 2 1
8 9 10 11
12
20
16 15
26
20
21
13
14
27
18
17
19
35
22
23

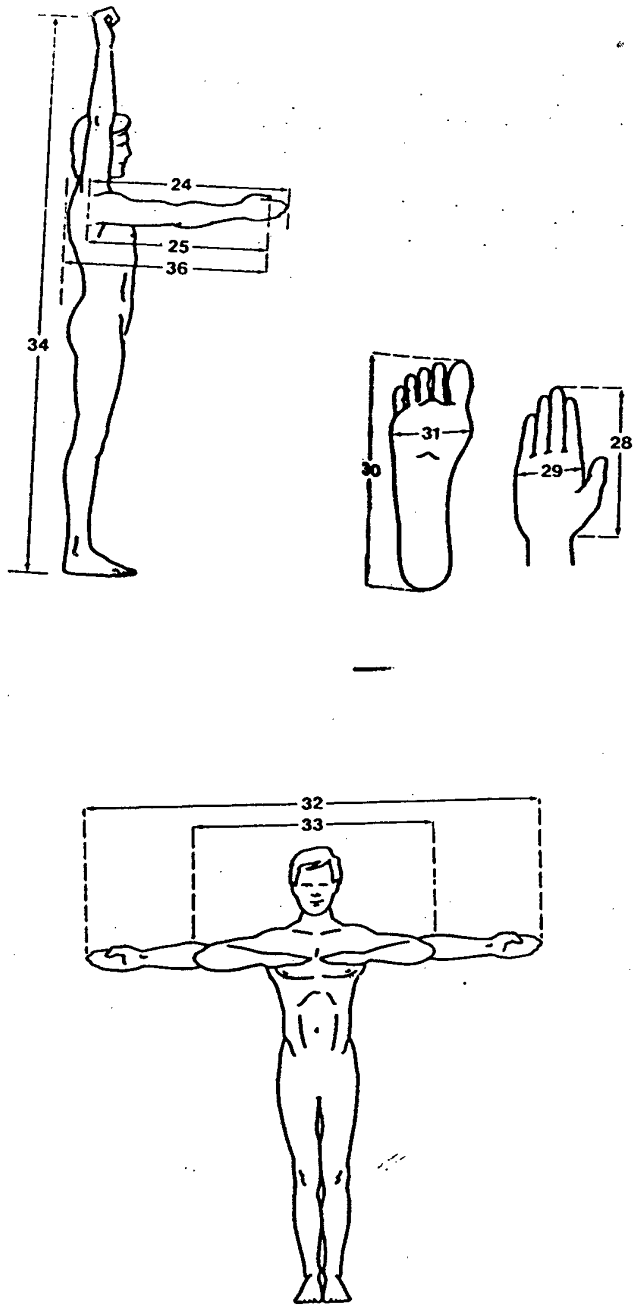


Figure 7. Static anthropometric dimensions
(Source: Bodyspace, Fig. 4.2, p. 74; Fig 4.3, p. 75; Fig 4.4, p. 76; Fig 4.5, p. 78; Fig 4.6, p. 79; Fig 4.7, p. 79; Fig 4.8, p. 80)

Table 2. Anthropometric estimates for Hong Kong Chinese adults (all dimensions in millimetres).
(Source: Bodyspace, Table 4.36, p. 118)

	Dimension	Men				Women			
		5th %ile	50th %ile	95th %ile	SD	5th %ile	50th %ile	95th %ile	SD
1.	Stature	1585	1680	1775	58	1455	1555	1655	60*
2.	Eye height	1470	1555	1640	52	1330	1425	1520	57*
3.	Shoulder height	1300	1380	1460	50	1180	1265	1350	51*
4.	Elbow height	950	1015	1080	39	870	935	1000	41*
5.	Hip height	790	855	920	41	715	785	855	42
6.	Knuckle height	685	750	815	40	650	715	780	41
7.	Fingertip height	575	640	705	38	540	610	680	44
8.	Sitting height	845	900	955	34	780	840	900	37*
9.	Sitting eye height	720	780	840	35	660	720	780	35*
10.	Sitting shoulder height	555	605	655	31	510	560	610	29*
11.	Sitting elbow height	190	240	290	31	165	230	295	38*
12.	Thigh thickness	110	135	160	14	105	130	155	14
13.	Buttock-knee length	505	550	595	26	470	520	570	30*
14.	Buttock-popliteal length	405	450	495	26	385	435	485	29*
15.	Knee height	450	495	540	26	410	455	500	27*
16.	Popliteal height	365	405	445	25	325	375	425	29*
17.	Shoulder breadth (bideltoid)	380	425	470	26	335	385	435	29*
18.	Shoulder breadth (biacromial)	335	365	395	19	315	350	385	22
19.	Hip breadth	300	335	370	22	295	330	365	21* (M)
20.	Chest (bust)depth	155	195	235	25	160	215	270	34
21.	Abdominal depth	150	210	270	36	150	215	280	39
22.	Shoulder-elbow length	310	340	370	19	290	315	340	16*
23.	Elbow-fingertip length	410	445	480	22	360	400	440	24*
24.	Upper limb length	680	730	780	30	615	660	705	26
25.	Shoulder-grip length	580	620	660	25	525	560	595	22
26.	Head length	175	190	205	8	160	175	190	9
27.	Head breadth	150	160	170	7	135	150	165	8
28.	Hand length	165	180	195	9	150	165	180	9*
29.	Hand breadth	70	80	90	5	60	70	80	5*
30.	Foot length	235	250	265	10	205	225	245	11*
31.	Foot breadth	85	95	105	5	80	85	90	4*
32.	Span	1480	1635	1790	95	1350	1480	1610	80*
33.	Elbow span	805	885	965	48	690	775	860	51
34.	Vertical grip reach (standing)	1835	1970	2105	83	1685	1825	1965	86
35.	Vertical grip reach (sitting)	1110	1205	1300	58	855	940	1025	51
36	Forward grip reach	640	705	770	38	580	635	690	32

TABLE 1-2. RECENT ANTHROPOMETRIC DATA ON INTERNATIONAL POPULATION SAMPLES: AVERAGE AND STANDARD DEVIATION (ALL IN CM BUT WEIGHT IN KG)

	Sample size *N*	Stature	Sitting height	Knee height, sitting	Weight
Algerian females (Mebarki and Davies, 1990)	666	157.6 (5.56)	79.5 (5.01)	48.7 (3.61)	61.3 (12.9)
Brazilian males (Ferreira, 1988; cited by Al-Haboubi, 1991)	3076	169.9 (6.7)	—	—	—
Chinese females (Singapore) (Ong, Koh, Phoon, and Low, 1988)	46	159.8 (5.8)	85.5 (3.1)	—	—
Cantonese males (Evans, 1990)	41	172.0 (6.3)	—	—	60.0 (6.2)
Egyptian females (Moustafar, Davies, Darwich, and Ibraheem, 1987)	4960	160.6 (7.18)	83.8 (4.30)	49.9 (2.51)	62.6 (4.37)
Indian males (farmers) (Nag, Sebastian, and Mavlankar, 1980)	13	157.6 (1.7)	—	—	44.6 (1.4)
Indonesian females	468	151.6 (5.4)	71.9 (3.4)	—	—
Indonesian males (Sama'mur, 1985; cited by Intaranont, 1991)	949	161.3 (5.6)	87.2 (3.7)	—	—
Irish males (Gallwey and Fitzgibbon, 1991)	164	173.1 (5.83)	91.1 (3.03)	50.8 (2.77)	73.9 (8.66)
Italian females	753	161.0 (6.4)	85.0 (3.4)	49.5 (3.0)	58.0 (8.3)
Italian males (Coniglio, Fubini, Masali, Masiero, Pierlorenzi and Sagone, 1991)	913	173.3 (7.1)	89.6 (3.6)	54.1 (3.0)	75.0 (9.6)
Jamaican females	30	174.9	85.6	—	67.6
Jamaican males (Camey, Aghazadeh, and Nye, 1991)	123	164.8	83.2	—	61.4
Malay females (Ong, Koh, Phoon, and Low, 1988)	32	155.9 (6.6)	83.1 (3.9)	—	—
Saudi-Arabian males (Dairi, 1986; cited by Al-Haboubi, 1991)	1440	167.5 (6.1)	—	—	—
Sri Lankan females	287	152.3 (5.9)	77.4 (2.2)	—	—
Sri Lankan males (Abeysekera, 1985; cited by Intaranont, 1991)	435	163.9 (6.3)	83.3 (2.7)	—	—
Sudanese males					
Villagers	37*	168.7 (6.3)	—	—	57.1 (7.6)
City dwellers	16*	170.4 (7.2)	—	—	62.3 (13.1)
	48**	166.8	—	—	51.3
Soldiers	21*	173.5 (7.1)	—	—	71.1 (8.4)
	104**	172.8	—	—	60.0
*(Elkarim, Sukkar, Collins, and Dore, 1981) **(Ballal et al., 1982; cited by Intaranont, 1991)					
Thai females	250*	151.2 (4.8)	—	—	—
	711**	154.0 (5.0)	81.7 (2.7)	—	—
Thai males*	250*	160.7 (2.0)	—	—	—
	1478**	165.4 (5.9)	87.2 (3.2)	—	—
*(Intaranont, 1991) **(NICE; cited by Intaranont, 1991)					
Turkish females					
Villagers	47	156.6 (5.2)	79.2 (3.8)	48.6 (2.7)	69.1 (13.8)
City dwellers (Goenen, Kalinkara, and Oezgen, 1991)	53	156.3 (5.5)	78.6 (0.5)	47.1 (0.5)	65.9 (13.0)
Turkish males (soldiers) (Kayis and Oezok, 1991)	5108	170.2 (6.0)	88.8 (3.4)	51.3 (2.8)	63.3 (7.3)

Body measurements for Region 17 (South China)

Measurement	Percentile:	Men 5	Men 50	Men 95	Women 5	Women 50	Women 95	Min.	Max.
Stature		1 610	1 660	1 710	1 430	1 520	1 590	1 430	1 710
Sitting height		790	840	890	740	790	840	740	890
Eye height, sitting		690	740	790	650	690	740	650	790
Forward reach (fingertips)		760	800	840	690	730	760	690	840
Shoulder breadth (bideltoid)		365	400	425	335	360	395	335	425
Shoulder breadth (biacromial)		340	360	395	310	330	355	310	395
Hip breadth (standing)		285	310	330	305	330	360	285	360
Knee height		490	505	520	415	460	490	415	520
Lower leg length (popliteal height)		370	400	430	330	370	400	330	430
Elbow-grip length		315	335	360	280	305	335	280	360
Buttock-knee length		500	540	580	460	490	520	460	580
Buttock-heel length		970	1 010	1 040	880	940	1 000	880	1 040
Hip breadth (sitting)		295	320	340	330	370	410	295	410
Hand length		165	180	195	150	165	180	150	195
Hand breadth		90	95	100	80	85	90	80	100
Foot length		230	245	260	210	225	240	210	260
Head circumference		530	550	570	510	535	555	510	570
Head length		180	190	200	170	180	190	170	200
Head breadth		140	150	160	135	145	150	135	160

8582d

Body measurements for Region 18 (South-East Asia)

Measurement	Percentile:	Men 5	Men 50	Men 95	Women 5	Women 50	Women 95	Min.	Max.
Stature		1 530	1 630	1 720	1 440	1 530	1 620	1 440	1 720
Sitting height		790	840	900	750	800	850	750	900
Eye height, sitting		680	730	780	660	700	740	660	780
Forward reach (fingertips)		730	780	820	690	730	780	690	820
Shoulder breadth (bideltoid)		380	410	430	340	380	410	340	430
Shoulder breadth (biacromial)		320	370	420	300	335	370	300	420
Hip breadth (standing)		285	310	330	285	315	360	285	360
Knee height		465	495	525	430	460	485	430	525
Lower leg length (popliteal height)		380	415	445	365	385	405	365	445
Elbow-grip length		300	325	360	280	305	340	280	360
Buttock-knee length		490	530	570	470	500	530	470	570
Buttock-heel length		910	970	1 025	860	915	970	860	1 025
Hip breadth (sitting)		290	315	340	330	365	400	290	400
Hand length		160	175	185	155	165	175	155	185
Hand breadth		75	80	85	70	75	80	70	85
Foot length		220	235	250	210	220	235	210	250
Head circumference		530	565	595	500	530	560	500	595
Head length		175	185	195	165	175	185	165	195
Head breadth		135	145	155	130	135	145	130	155

Region 17: South China

China (southern part)
Hong Kong
Macao
Taiwan, China

Population of the region: 425 million

Data sources:

Chen, K.P. et al. (1963)
Courtney, A.J. (1984)
Courtney, A.J. and Ng, M.K. (1984)
Kimura, K. and Tsai, C. (1967, 1968)
Nakata, S. (1987b)
Tsai, Tsuli et al. (1969)
Wang, Chien-Che (1984)
Yuan, Chung-Yin (1982)

Region 18: South-East Asia

Brunei
Democratic Kampuchea
Indonesia
Lao People's Democratic Republic
Malaysia
Myanmar
Philippines
Singapore
Thailand
Viet Nam

Population of the region: 391 million

Data sources:

Anh, Tran and Tien-Loi, Vu (1966)
Chabeuf, M. (1967)
Huard, P. et al. (1962)
Krukoff, S. (1966)
Kurth, G. and Lam, T.H. (1969)
Lee, J. et al. (1981)
Lourie, J.A. and Taufa, T. (1986)
Novak, L.P. (1970)
Olivier, G. (1956)
Ringrose, H. and Zimmet, P. (1979)
Rutishauser, I.H.E. and McCay, H. (1986)

Department of Industrial Engineering & Engineering Management
Hong Kong Univ. of Science & Tech.
Clear Water Bay, Kowloon
Email: ravindra@ust.hk

Principles and Practice of Anthropometry

References:

ANTHROPOMETRIC SOURCE BOOK (1978). NASA Reference Publication 1024. Houston: NASA Scientific and Technical Information Office.

Volume 1: Anthropometry for Designers

Volume 2: A handbook of anthropometric data

Volume 3: Annotated bibliography of anthropometry

Clauser, C., Tebbetts, I., Bradtmiller, B., Ervin, C., Annis, J., McConville, J., and Gordon, C. (1987). Measurer's handbook: US Army anthropometric survey, 1987-1988 (draft, U.S. Army contract DAAK60-86-C-0128). Yellow Springs, OH: Anthropology Research project, Inc.

Cooklin, G. (1990). Pattern grading for women's clothes. Melbourne: BSP Professional Books.

Diffrient, N., Tilley, A., and Bardajy, J. C. (1974). Humanscale 1/2/3. Cambridge, MA: MIT Press

Diffrient, N., Tilley, A., and Harman, D. (1981). Humanscale 4/5/6/7/8/9. Cambridge, MA: MIT Press.

Garrett, J. W. and Kennedy, K. W. (1971). A collation of anthropometry (AAMRL TR-68-1). Wright-Patterson Air Force Base, OH: Aerospace Medical Research Laboratory.

Lohman, T. G., Roche, A. F., and Martorell, R. (1988). Anthropometric Standardization Reference Manual. Champaign, IL: Human Kinetics Books.

Pheasant, S. (1988). Bodyspace. London: Taylor and Francis.

Taylor, P. J. and Shoben, M. M. (1990). Grading for the fashion industry. London: Stanley Thornes.

White, R. M. (1982). Comparative anthropometry of the foot. Natick, MA: US Army Natick Research & Development labs. Report Number NATICK/TR-83/010.

4. VISUAL INDEX OF FOOT MEASUREMENTS

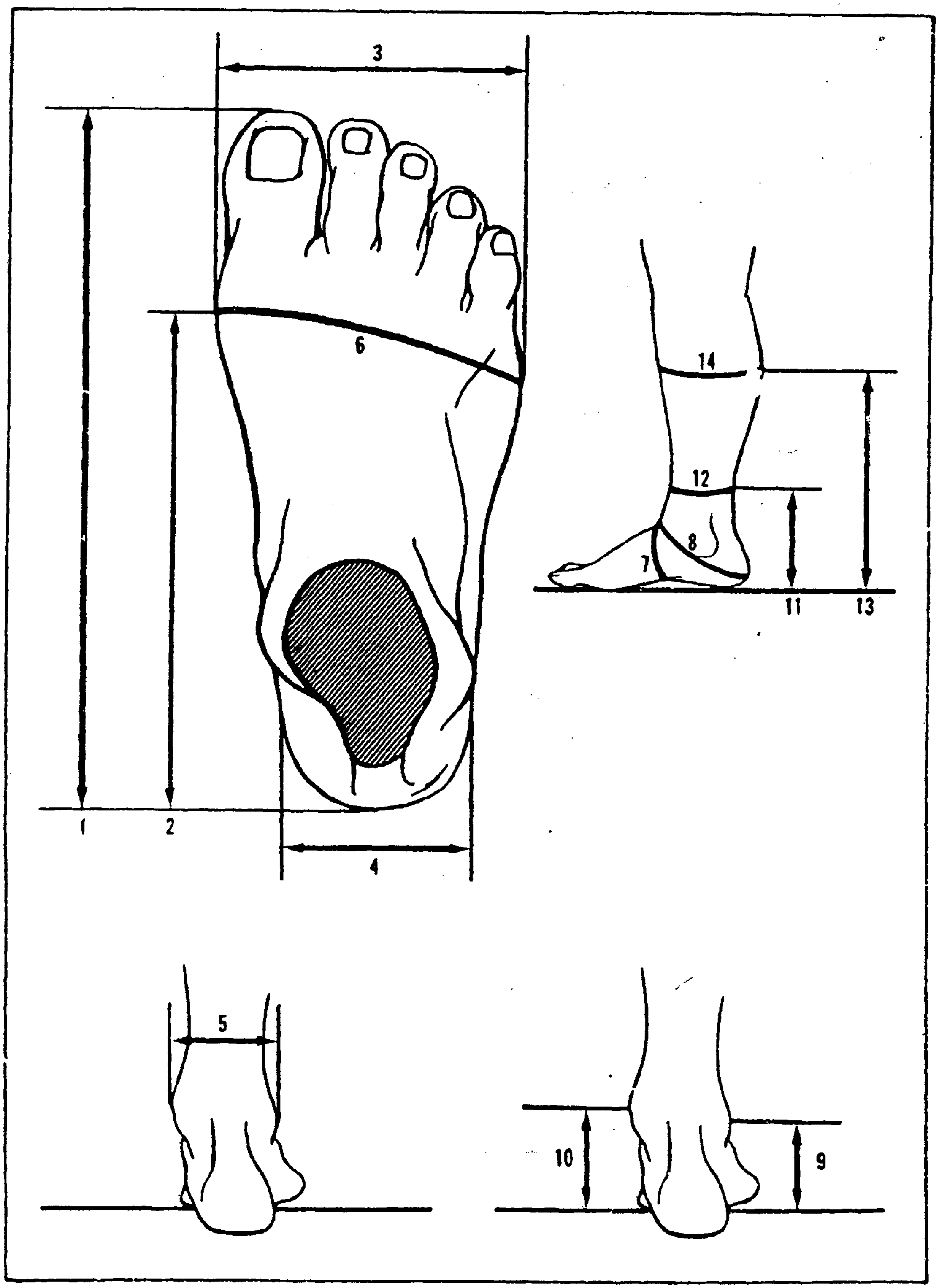


Figure 1. Foot Measurements

5. DEFINITIONS OF FOOT MEASUREMENTS

1 **Foot Length** – the length of the foot from the heel to the tip of the longest toe.

2 **Instep Length** – the distance from the heel to the center of the inner "ball" of the foot (first metatarsal–phalangeal joint).

3 **Foot Breadth** – the maximum breadth of the foot, measured at right angles to its long axis.

4 **Heel Breadth** – the maximum breadth of the heel, measured behind the projections of the "ankle bones" (lateral and medial malleoli).

5 **Bimalleolar Breadth** – the breadth between the projections of the "ankle bones" (lateral and medial malleoli).

6 **Ball of Foot Circumference** – the circumference of the foot, measured with the tape passing over the medial and lateral "balls" of the foot (metatarsal–phalangeal joints).

7 **Instep Circumference** – the vertical girth of the foot at the instep, measured with the tape passing under the foot and over the junction of the foot and the leg.

8 **Heel–Ankle Circumference** – the diagonal girth of the foot, measured with the tape passing under the tip of the heel and over the instep at the junction of the foot and the leg.

9 **Lateral Malleolus Height** – the vertical distance from the floor to the midpoint of the outer "ankle bone" (lateral malleolus).

10 **Medial Malleolus Height** – the vertical distance from the floor to the midpoint of the inner "ankle bone" (medial malleolus).

11 **Ankle Height** – the vertical distance from the floor to the level of the minimum circumference of the lower leg.

12 **Ankle Circumference** – the minimum circumference of the lower leg, measured above the "ankle bones" (lateral and medial malleoli).

13 **Calf Height** – the vertical distance from the floor to the level of the maximum circumference of the lower leg.

14 **Calf Circumference** – the maximum circumference of the lower leg.

Foot Length, measured from the back of the heel to the tip of the longest toe, represents the basic overall length of the foot. This is sometimes referred to as stick length. (It may be noted that the second toe is longer than the great toe in about seven percent of U. S. Army men.) Instep Length (or Ball Length) is the distance from the back of the heel to the center of the inner "ball" of the foot (or the first metatarsal–phalangeal joint). This is an important dimension of the foot in the fitting of shoes, since it represents the location of the "break" in the shoes when walking. The difference between Foot Length and Instep Length indicates the length of the toes; this also is an important area in shoe fitting in that adequate space must be allowed within the shoe for the length of the toes. Foot Breadth is the maximum breadth of the foot; it is usually measured at right angles to the long axis of the foot, but it also may be measured on the diagonal between the 1st and 5th metatarsal–phalangeal joints. Heel Breadth, measured behind the projections of the "ankle bones" (the lateral and medial malleoli), is also an important dimension for lasts and shoes since the shoe should "grip" the heel when properly fitted in order to avoid the heel of the foot slipping out of the shoe. Ball of Foot Circumference is the girth of the foot, measured over the medial and lateral "balls" of the foot (metatarsal–phalangeal joints). This is an important girth measurement as it reflects not only the breadth of the foot but also its volume. Instep Circumference is the girth of the foot in the instep area. Heel–Ankle Circumference is the girth of the foot, measured diagonally under the tip of the heel and over the instep at the junction of the foot and the leg. This is the greatest dimension of the foot which must be accommodated when donning and doffing boots without laces or zippers, such as rubber boots or the so-called Wellington boots. The Lateral and Medial Malleolar Heights are the vertical distances from the floor to the outer and inner "ankle bones" (or the lateral and medial malleoli). Ankle Circumference is the minimum girth of the lower leg, while Ankle Height is the vertical distance from the floor to the level of the ankle. Calf Circumference, the maximum girth of the lower leg, and Calf Height, the vertical distance from the floor to the level of the calf, are included with the foot measurements because of their importance in determining the opening and the height of various types of boots.

CHAPTER 1

Women's sizing and surveys

The problem of sizing arose with the development of the production of ready-made 'off-the-peg' garments at the turn of this century. If manufacturers were to cater for public demand in this way, a detailed investigation of the range of sizes within a country was needed. It was a long time before any serious efforts were made in this direction, but in 1940 a survey was set up in the United States to measure the American female. This survey covered a sample of 10,000 women using sixty measurements. A similar survey was carried out in the United Kingdom in 1950 using a sample of 5000 adult females and thirty-seven measurements. Other surveys have been undertaken in Europe, but the main surveys have been the American and British surveys. These produced very similar results and are now the main source of data for sizing and grading systems in these two countries.

The data and results of the British survey were published in a book called *Women's Measurements and Sizes* by W. F. F. Kemsley (HMSO 1957). In this book there are comments and a number of comparisons with the American survey, and also with the Dutch and the Ministry of Food surveys. One of the main results of the survey was that it produced a set of measurements for the 'statistically average woman'.

This average figure, therefore, represents the highest percentage of the population, and radiating out from it are progressively rarer combinations. The survey team recommended the categorization of the survey sizing data in the form of several size charts. These were arrived at by taking three height and six bust categories with approximately eight hip sizes of 5.0 cm increment in each (as in Table 1), which gives a total of 126 sizes spread over sixteen categories of size charts.

Table 2 shows the sizes and percentage of population in each category, totalling 98 per cent

Table 1 126 sizes recommended by the survey to cover 98 per cent of the population

Bust girth in relation to hip girth		Short 150.0 cm	Medium 160.0 cm	Tall 170.0 cm
15.0 cm smaller than hip	Very small bust	5 sizes	6 sizes	5 sizes
10.0 cm smaller than hip	Small bust	8 sizes	8 sizes	7 sizes
5.0 cm smaller than hip	Medium bust	10 sizes	11 sizes	8 sizes
Same as hip	Full bust	10 sizes	11 sizes	8 sizes
5.0 cm larger than hip	Large bust	9 sizes	10 sizes	5 sizes
10.0 cm larger than hip	Extra large bust	—	5 sizes	—

Table 2 Sizes and percentage of the population in each category, totalling 98 per cent of the population

Bust	Short 150.0 cm	Medium 160.0 cm	Tall 170.0 cm
Very small bust	12–20 (1%)	12–22 (3%)	14–22 (2%)
Small bust	10–24 (5%)	10–24 (12%)	12–24 (5%)
Medium bust	8–26 (9%)	8–28 (20%)	10–24 (7%)
Full bust	8–26 (7%)	8–28 (14%)	10–24 (4%)
Large bust	8–24 (2%)	8–26 (5%)	10–18 (1%)
Extra large bust	—	12–20 (1%)	—

Table 3 Reduced table of sixty-three sizes covering 80 per cent of the population

	Short	Medium	Tall
Small bust	Size 10–22	Size 10–22	Size 10–22
Medium bust	Size 10–22	Size 10–22	Size 10–22
Full bust	Size 10–22	Size 10–22	Size 10–22

of the population. The other 2 per cent of the population are considered, by statistical standards, to be outside the normal range and are discarded in order not to distort the final results.

The sixteen categories can be reduced to nine and the number of sizes reduced, thereby discarding the less populated areas, as shown in Table 3.

Table 3 illustrates the reduced categories with seven sizes in each, totalling sixty-three sizes.

Table 4 shows the percentage of population per hip size and three bust categories covering all heights.

It follows that the sixty-three sizes in Table 4 cover 83 per cent of the population, and are valuable as a guide and reference to all clothing manufacturers.

For detailed information it is advisable to obtain the survey book but there is always the danger of getting lost in statistical analyses. It is for this reason that we have commented only briefly on the survey in this book, but as a subject in its own right it can be quite absorbing.

Finally it must be noted that the survey covered a wide range of ages from 18 to 65 years. The data was divided into three age categories:

1 18 to 29 years
2 30 to 44 years
3 45 to 65 years

The size charts in this book are for all the age groups combined. Table 5 gives a complete list of measurements showing the statistically average figure for each age group.

BASIC SIZE CHARTS

The size charts in the survey provide vital information which enables manufacturers to select and cater for specific areas of the population. It is obvious that the whole population cannot be covered by a single manufacturer and it is even more impossible for a retailer to stock such a vast range of sizes. This must be qualified, however, by saying, first, that the type of garment will have a great influence on the number of sizes required and, second, the type of material will also affect the sizing. A loose fitting garment will not require as many sizes as a skin-tight garment, and a woven fabric will require more tolerances than a stretch fabric, and will therefore influence the number of sizes needed.

Another aspect of the situation is the number of styles needed. If only a single style is required, a manufacturer and retailer would find it economic to stock a greater range of sizes. Conversely, if many styles are required the opposite applies. This, in turn, is affected by the number of different colours and material designs used.

To narrow down options available, a manufacturer will usually select a limited area of the market and cater only for that area. Having decided on the area, the next step is to construct a basic size chart for that market. The market will be chosen by:

1 The age group
2 The figure size
3 The type of garment

The first step in constructing a size chart is to decide the increments between the sizes of the major girth which is selected to be the size indicator or code. Where there is a hip girth in the garment it is generally used as the code, otherwise the bust girth is used – except in brassiere manufacturing when the rib-cage girth is used. It is more convenient if the difference between sizes is constant.

Table 4 The percentages of population per hip size in three bust categories covering all heights

Size	10	12	14	16	18	20	22	Total
Hip cm	87.0	92.0	97.0	102.0	107.0	112.0	117.0	
Small bust %	0.9	4.0	6.4	5.4	3.2	1.5	1.0	22.4
Medium bust %	3.1	8.6	10.0	7.2	4.0	1.9	1.1	35.9
Full bust %	3.0	6.2	6.3	4.4	2.5	1.3	1.0	24.7
Total %	7.0	18.8	22.7	17.0	9.7	4.7	3.1	83.0

Table 5 Statistical averages by age

Area		Age categories 18–29	30–44	45–64
1	Height	161.0	160.0	157.5
2	Weight (pounds)	126.6	134.5	143.8
3	Hip	95.0	97.5	102.4
4	Bust	89.5	93.0	99.0
5	Waist	64.0	68.9	76.4
6	Chest	84.0	86.4	90.0
7	Top hip (11.0 cm from waist)	85.0	88.8	95.3
8	Rib cage	nil	nil	nil
9	Neck	38.0	38.5	39.0
10	Bicep	27.6	28.9	30.4
11	Elbow	nil	nil	nil
12	Wrist	nil	nil	nil
13	Thigh	nil	nil	nil
14	Knee	35.0	35.4	36.0
15	Calf	33.5	34.0	34.5
16	Ankle	nil	nil	nil
17	X-chest	31.8	32.5	33.3
18	X-back	33.3	34.0	34.7
19	Shoulder length	11.7	11.7	11.7
20	Scye width	11.4	11.9	12.4
21	Scye depth	18.4	18.8	19.2
22	Bust width	19.5	20.0	21.0
23	Nape to bust	34.8	36.0	39.0
24	Nape to waist over bust	52.0	52.0	52.0
25	Nape to waist centre back	38.2	37.8	37.0
26	Nape to hip	60.0	59.5	58.0
27	Nape to knee	95.6	95.0	93.8
28	Nape to floor	137.8	137.0	135.0
29	Sleeve length (outer)	58.4	58.0	57.7
30	Sleeve length (inner)	44.8	44.2	43.2
31	Abdominal seat diameter	24.0	25.4	27.9
32	Hip width	33.0	33.7	34.9
33	Body rise	29.0	29.7	30.9
34	Shoulder angle (degrees)	20.2	20.2	20.7

Table 6 Basic size chart hip increments

Size	10	12	14	16	18	20	22	Increment
Hip	87	92	97	102	107	112	117	5.0 cm

The sizes and increments must come within the recommended British Standards BS 3666 (see pages 21–5). The general practice in the past has been to use 2 in, but now its equivalents, 5.0 cm and 50 mm, are used. However, in some cases, in order to remain within the Standard, a 4.0 cm or a 6.0 cm increment is used for some sizes, or a mixture of all three can be used, keeping, if possible, to a constant increment, especially over a 10–22 size range.

The British Standard is very flexible. Its aim is to ensure that, for example, a size 12 shall be within a certain minimum and maximum measurement. Basically it gives a scope of 4.0 cm between the smallest and largest hip and bust within a size, which, therefore, means that a size may vary considerably. In addition, the garment's inbuilt tolerances may increase the variations within a size still further. The Standard is, therefore, fairly flexible. The main reason for this is that it must enable the manufacturer to cater for the population as a whole, which, as we have seen, consists of nine major size categories, and this is why the Standard only quotes hip, bust and height measurements. (If a tighter Standard was required, then a Standard for each of the nine categories would be needed.) Most manufacturers will, however, select the area of the market that offers the richest rewards. This area, size wise, is immediately around the statistically average figure, as can be seen by studying Tables 2 and 4. The majority of the population are either size 12, 14 or 16 in the medium height range, and this accounts for the fact that many shops only stock these sizes. It is also the reason why the state of grading in industry is so limited because, only having to operate over a range of three sizes, the crudest methods of grading can be used. It must be said that this is not the case in all sections of the industry; some areas have a very high degree of grading expertise, particularly in outerwear.

Table 6 shows the hip sizes and increments that have been chosen to form the basis of the size chart used in this book. The hip sizes have been selected because they are typical of the clothing industry. This basic chart gives a 5.0 cm constant increment and conforms to the British Standard. These hip sizes are roughly in the middle range of the Standard. A few alternative examples are given in Table 7 with non-constant increments. Table 7 also shows examples of hip sizes which conform to British Standards and illustrates the difference between the sizes, or the increments, as they are known by the grader.

HEIGHT ANALYSIS

The next factor to be considered in the basic size chart is height, i.e., which height to cater for and what height increase there should be between sizes, if any. The survey divided the population into three basic height groups:

1 Short – below 160.0 cm
2 Medium – from 160.0 – 170.0 cm
3 Tall – above 170.0 cm

The manufacturer has to choose which height group to cater for. It is not possible to cover the whole height range in one size chart and, there-

Table 7 Examples of basic size chart hip increments, which conform to BS 3666, including increments of 4.0 and 6.0 cm

	Size 10	12	14	16	18	20	22
Hip	87.0	92.0	97.0	102.0	107.0	112.0	117.0
Increment	5.0	5.0	5.0	5.0	5.0	5.0	—
Hip	88.0	92.0	96.0	100.0	104.0	110.0	116.0
Increment	4.0	4.0	4.0	4.0	6.0	6.0	—
Hip	87.0	91.0	95.0	100.0	105.0	110.0	115.0
Increment	4.0	4.0	5.0	5.0	5.0	5.0	—
Hip	87.0	93.0	99.0	104.0	109.0	114.0	119.0
Increment	6.0	6.0	5.0	5.0	5.0	5.0	—
Hip	89.0	94.0	99.0	104.0	109.0	114.0	119.0
Increment	5.0	5.0	5.0	5.0	5.0	5.0	—
Hip	88.0	92.0	96.0	100.0	105.0	110.0	115.0
Increment	4.0	4.0	4.0	5.0	5.0	5.0	—
Hip	90.0	94.0	98.0	102.0	106.0	110.0	115.0
Increment	4.0	4.0	4.0	4.0	4.0	5.0	—
Hip	87.0	91.0	96.0	101.0	106.0	111.0	116.0
Increment	4.0	5.0	5.0	5.0	5.0	5.0	—

fore, most manufacturers gravitate towards the statistical average. Table 8 shows the distribution of the population according to their height, and it gives the manufacturer an idea of the numbers that can be expected in the market that has been chosen.

It should be noted that the British Standard requires an indication of height group on garment labelling; a prefix 'S' for short and 'T' for tall. No prefix is required for the medium height group.

Another consideration is whether or not to incorporate height in the size chart, that is, whether to increase height with girth. The survey indicates that height does not increase with girth and so, according to the conclusions of the survey, height should not increase with size. However, many manufacturers would argue that if the height increases with girth then the market will widen and more of the population can be served because a garment can be shortened if too long. It is more difficult to lengthen a garment unless, of course, large hems are included, but this is not always possible. These decisions must, however, be made by the individual companies.

In the early 1950s, when the survey data was first used, it seemed that the nape to waist measurement indicated in the survey was too short. In fact the average measurement given was correct but the percentage with a longer nape to waist measurement was not catered for. This led to a loss of sales because a short nape to waist is almost certain to be rejected, whereas a garment which is too long can be sold quite easily by experienced staff, either by offering to shorten the garment or by quickly introducing a blouson effect! This led manufacturers to lengthen the nape to waist measurement to around 40.0 cm for size 12 and to grade a 0.6 cm height increment per size. So it will be found that most size 12 stands and size charts are designed for this length of bodice. This brings into focus an important corner-stone of grading. It is possible to grade for:

1 Girth only
2 Height only
3 Girth and height combined

This is discussed more fully on pages 18–19.

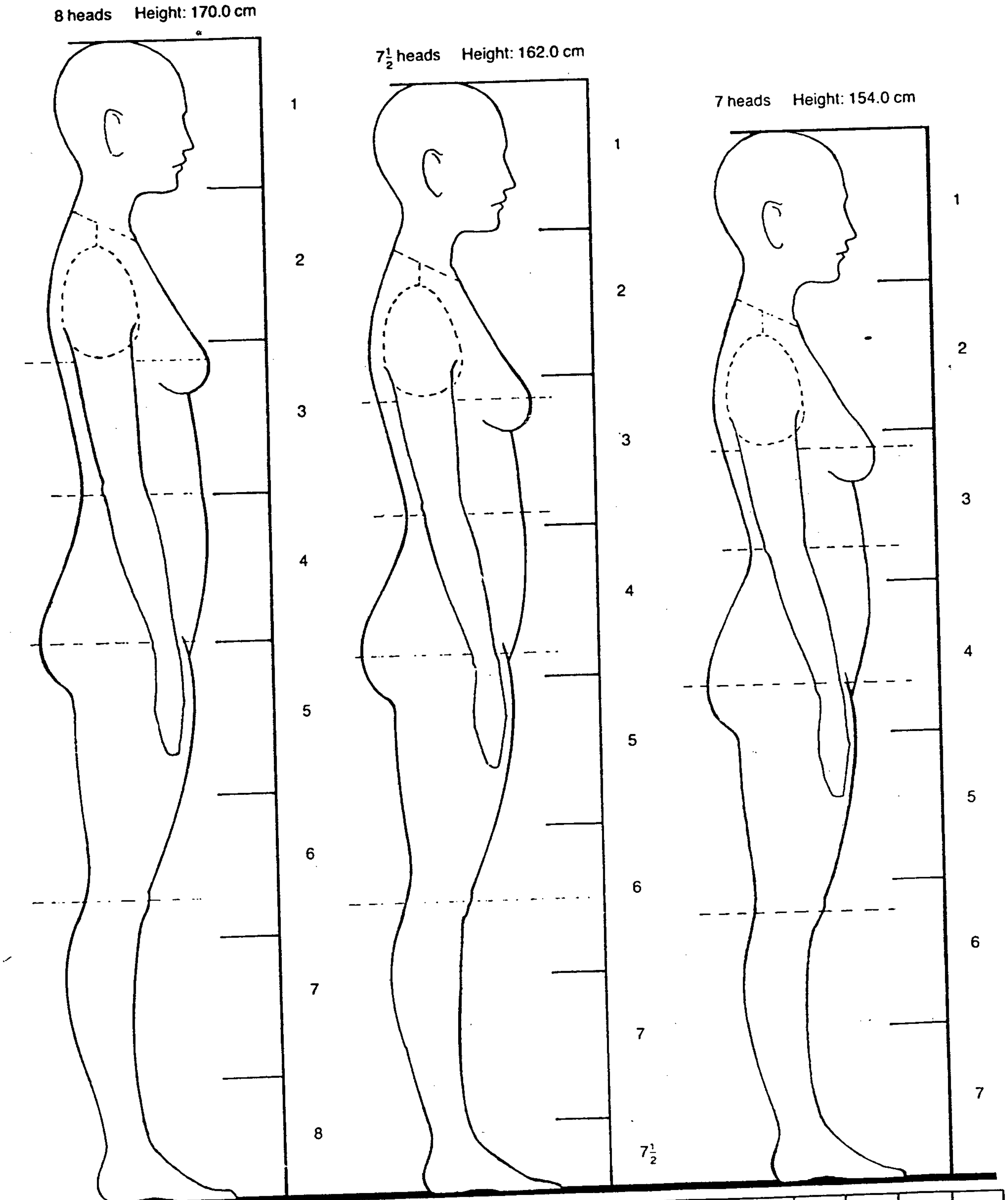
For the purposes of this book combined height and girth grades are used on the sample styles throughout, except for one example of height only.

HEIGHT GRADE

To introduce height, the increase between sizes has to be distributed evenly over the whole figure. This is borne out by the survey. Some may argue that more must go into the leg than the torso, or vice versa. However, it has been the practice to divide the body into eight equal parts and apportion an eighth of the height increase to each. This

Table 8 Distribution of population by height

Height	Number in sample	Percentage	Population in millions
Under 145.0 cm	39	1	0.1
145.0 and 147.0 cm	273	6	1.0
150.0 and 152.0 cm	798	18	2.9
155.0 and 157.0 cm	1176	28	4.4
160.0 and 162.0 cm	1206	28	4.4
165.0 and 167.0 cm	584	13	2.2
170.0 and 172.0 cm	217	5	0.8
175.0 cm and above	56	1	0.2
Totals	4349	100	16.0



Grade options per head	0.1	0.2	0.3	0.4		0.1	0.2	0.3	0.4		0.1	0.2	0.3	0.4
Total	0.8	1.6	2.4	3.2		0.75	1.5	2.25	3.0		0.7	1.4	2.1	2.8

Figure 1 The three height categories – tall, medium and short – showing the head divisions of the body

Table 9 Basic size chart (used as the basis of the size chart for this book)

Size	10S	12	14	16	18	20T	22T	Increment
Height	159.6	162.0	164.4	166.8	169.2	171.6	173.0	2.4
Hip	87.0	92.0	97.0	102.0	107.0	112.0	117.0	5.0
Bust	82.0	87.0	92.0	97.0	102.0	107.0	112.0	5.0
Waist	60.0	65.0	70.0	75.0	80.0	85.0	90.0	5.0

practice had its origin in the imperial measurement system where an eighth of an inch was widely used and an eighth of body height roughly coincided with the size of the head, and the measurement from the top of the head to the waist was, conveniently, three-eighths of body height. As a matter of interest, the head only goes into the height eight times in the tall group where the height is above average. In Figure 1 the three height groups are illustrated to show the relationship between the head and other body proportions. Note that these drawings are to scale and that the head remains a constant size.

Height increase

Figure 1 shows three figure categories with height grade increment options. For this book the eight head figure has been selected with an overall increment of 2.4 cm per size. This amount corresponds to the 1 in increment which was widely used under the imperial system, although there is no logical reason for it to be adopted other than convention.

Note: If 2.4 cm is used, the height range will extend into the British Standard tall range in the larger sizes and short range in size 10. The total height increase is thus divided into eight equal parts of 0.3 cm for each area of the body.

CHOICE OF BUST AND WAIST SIZE

The bust used is medium, that is 5.0 cm less than the hip. There is, once again, a choice of three categories (see Table 3). The waist chosen is an average one based on the survey statistics.

Table 9 is the final basic size chart which is used for sales and retail requirements, and is used as the basis of the size chart for this book. The further development of the size chart will be for the use of technical staff producing the garments. For this, the survey is used extensively.

Figure 2 and Table 10 illustrate the statistically average figure showing the thirty-four measurements used for this book which constitute the full size chart. The drawings in Figure 2 are to scale.

Table 10 Measurements of the statistically average woman

Area		
1	Height	159.5
2	Weight (pounds)	130.5
3	Hip	98.8
4	Bust	94.2
5	Waist	70.3
6	Chest	87.0
7	Top hip (11.0 cm from waist)	90.2
8	Rib cage (under bust)	—
9	Neck	38.3
10	Bicep	29.2
11	Elbow	—
12	Wrist	—
13	Thigh	—
14	Knee	35.5
15	Calf	34.5
16	Ankle	—
17	X-chest	32.5
18	X-back	34.0
19	Shoulder length	11.7
20	Scye width	12.0
21	Scye depth	19.0
22	Bust width	20.3
23	Nape to bust	36.0
24	Nape to waist over bust	52.0
25	Nape to waist centre back	37.8
26	Nape to hip	59.5
27	Nape to knee	95.[illegible]
28	Nape to floor	137.0
29	Sleeve length (outer)	56.0
30	Sleeve length (inner)	44.0
31	Abdominal seat diameter	25.6
32	Hip width	33.4
33	Body rise	30.0
34	Shoulder angle (degrees)	20.5

Body measurements: no tolerances added to any chart data

To find the scale, divide the height of the drawin into 160.0 cm.

The size chart data from the survey is produc in Table 11, and is called an area incremen chart.

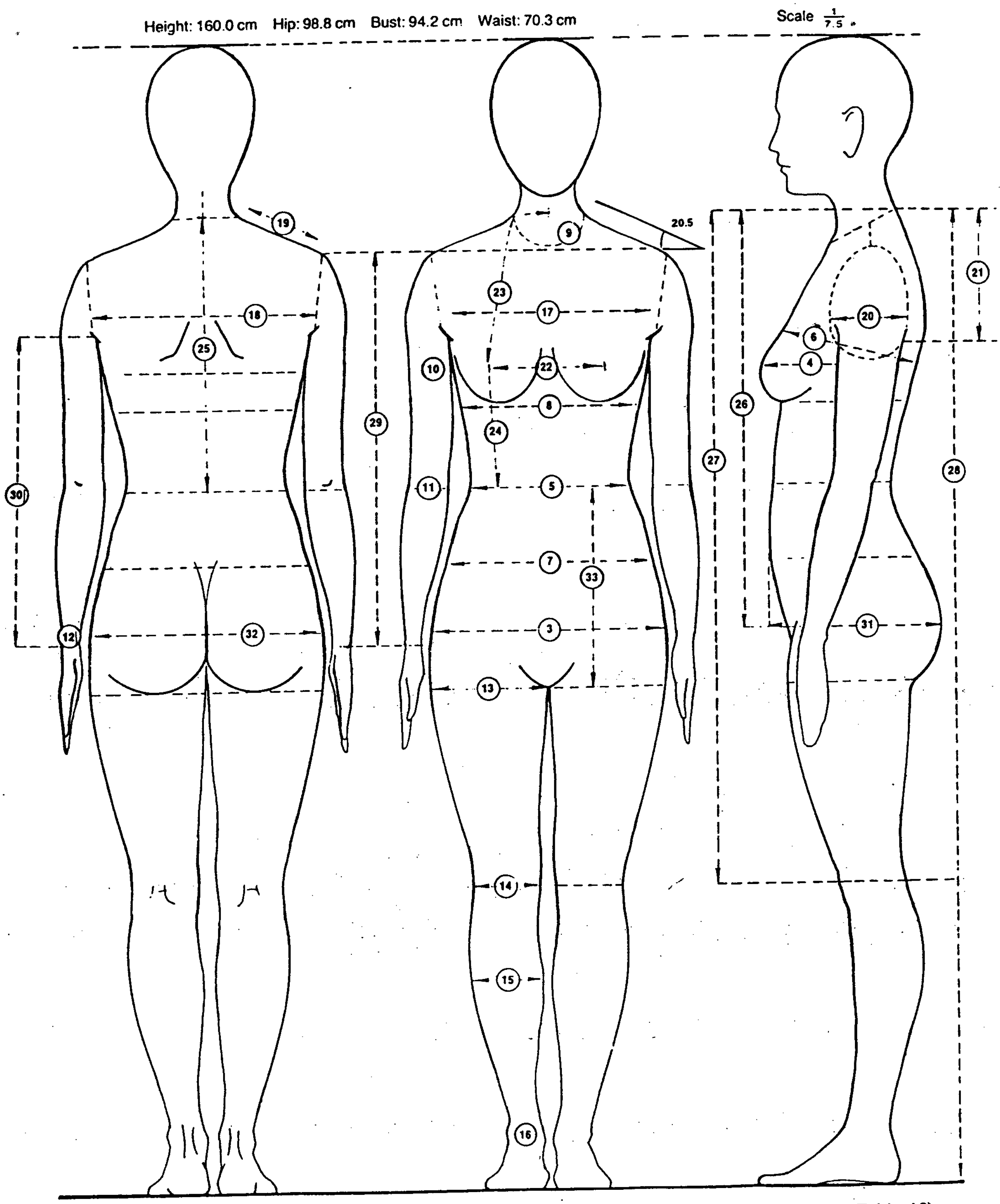


Figure 2 Scale illustration of the statistically average woman based on the British survey (see Table 10)

AREA INCREMENTS CHART

Table 11 is compiled directly from the survey data and comprises thirty-four measurements in the first column and uses the average figure data from Table 10 (which corresponds to a size 14). The second column shows increments for grading of girth only. The third column shows increments for grading of height only and the fourth column gives the sum of the previous two columns which results in increments used for grading height and girth together. The fifth and sixth columns explain how the girth and height increments are arrived at based on percentages obtained from the survey relating to hip and height. These percentages indicate the required girth and height increase for any of the thirty-four measurements in relation to the change in hip girth. As a 5.0 cm hip and 2.4 cm height has been chosen for the size chart then all the percentages will use these two figures to give the increase needed for one size.

Example: To find the neck increment
For girth only increase
14 per cent of 5.0 cm = 0.7 cm
For height only increase
8 per cent of 2.4 cm = 0.2 cm
Total for girth and height = 0.9 cm

Table 11 Area increments table based on survey data for the statistically average figure. Body measurements: increments are based on an increase of 5.0 cm girth and 2.4 cm height

Area		Statistic average figure	Increments for 5.0 cm girth and 2.4 cm height: Girth	Height	Girth and height	Percentage increase related to hip and height: Girth	Height
1	Height	159.5	nil	2.4	2.4	nil	100
2	Weight (pounds)	130.5	12.5	3.5	16	nil	nil
3	Hip	98.8	5.0	nil	5.0	100	nil
4	Bust	94.2	4.6	−0.2	4.4	92	−8
5	Waist	70.3	4.8	−0.5	4.3	98	−20
6	Chest	87.0	3.3	0.1	3.4	66	2
7	Top hip (11.0 cm from waist)	90.2	5.0	nil	5.0	100	nil
8	Rib cage (under bust)	no survey data					
9	Neck	38.3	0.7	0.2	0.9	14	8
10	Bicep	29.2	1.7	−0.1	1.6	34	−4
11	Elbow	no survey data					
12	Wrist	no survey data					
13	Thigh	no survey data					
14	Knee	35.5	1.2	0.2	1.4	24	8
15	Calf	34.5	1.2	0.2	1.4	24	8
16	Ankle	no survey data					
17	X-chest	32.5	0.8	0.1	0.9	16	4
18	X-back	34.0	1.0	0.1	1.1	20	4
19	Shoulder length	11.7	0.1	0.1	0.2	2	4
20	Scye width	12.0	0.7	−0.1	0.6	14	−4
21	Scye depth	19.0	0.4	0.1	0.5	8	4
22	Bust width	20.3	1.0	0.2	1.2	20	8
23	Nape to bust	36.0	1.3	0.1	1.4	28	4
24	Nape to waist over bust	52.0	0.6	0.6	1.2	12	24
25	Nape to waist centre back	37.8	nil	0.6	0.6	nil	24
26	Nape to hip	59.5	nil	0.9	0.9	nil	36
27	Nape to knee	95.0	nil	1.5	1.5	nil	60
28	Nape to floor	137.0	nil	2.1	2.1	nil	84
29	Sleeve length (outer)	56.0	nil	0.8	0.8	nil	32
30	Sleeve length (inner)	44.0	−0.3	0.6	0.3	−6	24
31	Abdominal seat diameter	25.6	1.9	−0.2	1.7	38	−8
32	Hip width	33.4	1.3	0.3	1.6	26	10
33	Body rise	30.0	1.0	0.1	1.1	20	4
34	Shoulder angle (degrees)	20.5	−0.25	0.25	0	nil	nil

Therefore, 7 mm is the size increment of the neck for a 5.0 cm hip increase on a girth only grade, and 2 mm is the size increment of the neck for a 2.4 cm increase on a height only grade. When grading for girth and height the two are added together, making 9 mm. The increments in this chart are inconvenient because they are odd quantities. For grading purposes it is better to round them off in order to make their application easier.

Table 12 is the area increments chart adapted from Table 11 by streamlining the measurements, and yet retaining the accuracy needed for an advanced system of grading.

Table 13 is the full size chart arrived at from the area increments chart for girth and height combined. This is the chart which will be used throughout this book and is a good example of a general purpose chart catering for the majority of the population. This chart is suitable for use on all types of clothing, giving body measurements which cover almost any eventuality. Note that the height goes from the top end of the short category into the lower end of the tall category. To comply with the British Standard BS 3666 an 'S' and 'T' are used to denote these categories. BS 3666 is reproduced on pages 21–5.

Table 12 Simplified area increments table. Body measurements for medium bust development: increments are based on an increase of 5.0 cm girth and 2.4 cm height

Area		Size 12	Girth only	Height only	Girth and height
1	Height	162.0	nil	2.4	2.4
2	Weight (pounds)	118.0	12.5	3.5	16.0
3	Hip	92.0	5.0	nil	5.0
4	Bust	87.0	5.0	nil	5.0
5	Waist	65.0	5.0	nil	5.0
6	Chest	82.0	3.6	nil	3.6
7	Top hip (11.0 cm from waist)	86.0	5.0	nil	5.0
8	Rib cage (under bust)	71.0	5.0	nil	5.0
9	Neck	37.0	0.8	0.2	1.0
10	Bicep	26.5	1.8	nil	1.8
11	Elbow	25.5	1.8	nil	1.8
12	Wrist	16.0	0.8	nil	0.8
13	Thigh	53.0	3.2	nil	3.2
14	Knee	34.0	1.2	0.2	1.4
15	Calf	33.0	1.2	0.2	1.4
16	Ankle	23.0	0.7	nil	0.7
17	X-chest	31.0	1.0	0.2	1.2
18	X-back	32.0	1.0	0.2	1.2
19	Shoulder length	11.5	0.1	0.1	0.2
20	Scye width	11.0	0.9	nil	0.9
21	Scye depth	18.1	0.5	0.1	0.6
22	Bust width	19.0	1.2	nil	1.2
23	Nape to bust	34.0	1.3	0.1	1.4
24	Nape to waist over bust	53.0	0.6	0.6	1.2
25	Nape to waist centre back	40.0	nil	0.6	0.6
26	Nape to hip	62.0	nil	0.9	0.9
27	Nape to knee	98.0	nil	1.5	1.5
28	Nape to floor	140.0	nil	2.1	2.1
29	Sleeve length (outer)	58.0	nil	0.9	0.9
30	Sleeve length (inner)	43.5	−0.4	0.8	0.4
31	Abdominal seat diameter	23.0	1.9	−0.2	1.7
32	Hip width	31.8	1.3	0.3	1.6
33	Body rise	29.0	1.0	0.1	1.1
34	Shoulder angle (degrees)	20.5	−0.25	0.25	nil

Table 13 Main size chart. Body measurements for medium bust development: increments are based o increase of 5.0 cm girth and 2.4 cm height

Area		Size 10S	12	14	16	18	20T	22T	Increr
1	Height	159.6	162.0	164.4	166.8	169.2	171.6	173.0	2
2	Weight (pounds)	102	118	134	150	166	182	198	16 l
3	Hip	87.0	92.0	97.0	102.0	107.0	112.0	117.0	5
4	Bust	82.0	87.0	92.0	97.0	102.0	107.0	112.0	5
5	Waist	60.0	65.0	70.0	75.0	80.0	85.0	90.0	5
6	Chest	78.4	82.0	85.6	89.2	92.8	96.4	100.0	3.6
7	Top hip (11.0 cm from waist)	81.0	86.0	91.0	96.0	101.0	106.0	111.0	5
8	Rib cage (under bust)	66.0	71.0	76.0	81.0	86.0	91.0	96.0	5
9	Neck	36.0	37.0	38.0	39.0	40.0	41.0	42.0	1.0
10	Bicep	24.7	26.5	28.3	30.1	31.9	33.7	35.5	1
11	Elbow	23.7	25.5	27.3	29.1	30.9	32.7	34.5	1
12	Wrist	15.2	16.0	16.8	17.6	18.4	19.2	20.0	0
13	Thigh	49.8	53.0	56.2	59.4	62.6	65.8	69.0	3.2
14	Knee	32.6	34.0	35.4	36.8	38.2	39.6	41.0	1
15	Calf	31.6	33.0	34.4	35.8	37.2	38.6	40.0	1
16	Ankle	22.3	23.0	23.7	24.4	25.1	25.8	26.5	0.7
17	X-chest	29.8	31.0	32.2	33.4	34.6	35.8	37.0	1.2
18	X-back (12.0 cm down from nape)	30.8	32.0	33.2	34.4	35.6	36.8	38.0	1
19	Shoulder length	11.3	11.5	11.7	11.9	12.1	12.3	12.5	0.2
20	Scye width	10.1	11.0	11.9	12.8	13.7	14.6	15.5	0
21	Scye depth	17.5	18.1	18.7	19.3	19.9	20.5	21.1	0
22	Bust width	17.8	19.0	20.2	21.4	22.6	23.8	25.0	1
23	Nape to bust	32.6	34.0	35.4	36.8	38.2	39.6	40.0	1.4
24	Nape to waist over bust	51.8	53.0	54.2	55.6	56.8	58.0	59.2	1
25	Nape to waist centre back	39.4	40.0	40.6	41.2	41.8	42.4	43.0	0
26	Nape to hip	61.1	62.0	62.9	63.8	64.7	65.6	66.5	0.9
27	Nape to knee	96.5	98.0	99.5	101.0	102.5	104.0	105.5	1.5
28	Nape to floor	137.9	140.0	142.1	144.2	146.3	148.4	150.5	2
29	Sleeve length (outer)	57.1	58.0	58.9	59.8	60.7	61.6	62.5	0
30	Sleeve length (inner)	43.1	43.5	43.9	44.3	44.7	45.1	45.5	0.4
31	Abdominal seat diameter	21.3	23.0	24.7	26.4	28.1	29.8	31.5	1.7
32	Hip width	30.2	31.8	33.4	35.0	36.6	38.2	39.8	1
33	Body rise	27.9	29.0	30.1	31.2	32.3	33.4	34.5	1
34	Shoulder angle (degrees)	20.5	20.5	20.5	20.5	20.5	20.5	20.5	nil

British Standard Specification for

Size designation of women's wear

0. Introduction

This British Standard is one of a series which deals essentially with the size designation of clothing, and is not directly concerned with sizing systems as such.

The primary aim of this and other British Standards in this series is the establishment of a size designation system that indicates (in a simple, direct and meaningful manner) the body size of the woman that a garment is intended to fit. Provided that the shape of her body (as indicated by the appropriate dimensions) has been accurately determined, this system will facilitate the choice of garments that fit.

The size designation system is based on body and not garment measurements. Choice of garment measurements is normally left to the designer and the manufacturer, who are concerned with style, cut and other fashion elements, and who must make due allowance for garments normally worn beneath a specific garment.

Definitions and body measurement procedure are prescribed in BS 5511 which is applicable to all categories of clothing.

1. Scope

This British Standard specifies a system of designating the size of women's outerwear and underwear garments that are classified as:

(a) covering the upper body, or

(b) covering the whole body, or

(c) covering the lower body only,

and it applies to civilian and uniform garments.*

Both the control dimensions on which the size designation system is based, and the method of indicating the size designation on a garment label, are specified.

This British Standard also contains details of a size coding scheme, which is to be included on the garment label together with the control dimensions.

2. References

The titles of the standard publications referred to in this Standard are listed on page 5.

3. Definitions

For the purposes of this British Standard, the definitions given in BS 5511 together with the following, apply.

woman. A female person whose growth in height is finished.

4. Control dimensions

4.1 Outerwear (including knitwear and swimwear). The control dimensions shall be as follows.

(a) Women's garments covering the upper or the whole body

Other than knitwear and swimwear	Knitwear	Swimwear
(1) Bust girth	Bust girth	Bust girth
(2) Hip girth		Hip girth
(3) Height		

(b) Women's garments covering the lower body only

(1) Hip girth
(2) Waist girth
(3) Outside leg length

4.2 Underwear (including nightwear, foundation garments and shirts). The control dimensions shall be as follows.

(a) Women's garments covering the upper body only

Other than foundation garments	Foundation garments
(1) Bust girth	Underbust girth
(2) –	Bust girth

(b) Women's garments covering the whole body

Other than foundation garments	Foundation garments
(1) Bust girth	Underbust girth
(2) Height	Bust girth
(3) –	Hip girth

Nightwear, 1-piece garments	Nightwear, 2-piece garments
(1) Bust girth	Bust girth
(2) Height	Hip girth
(3) –	Height

(c) Women's garments covering the lower body only

Other than foundation garments	Foundation garments
(1) Hip girth	Waist girth
(2) –	Hip girth

5. Size designation

5.1 The size designation of each garment shall comprise the control dimensions (see clause 4), in centimetres, of the intended wearer of that garment. Where practicable, the standard or the special pictogram, as given in BS 5511, should be used as a means of indicating the size designation. Where it is not practicable to use the pictogram, the control measurements shall be given, together with the descriptive

*Examples of garments covered by this British Standard are given in appendix A.

words such as bust girth, hip girth, etc. alongside in the order in which they are given in clause 4.

NOTE. The above requirements do not preclude the use, in exceptional instances of:

(a) size designations comprising only one or two of the applicable control dimensions;

(b) size designations shown as a range by stating the minimum and maximum control measurements separated by an oblique stroke or a hyphen.

5.2 Garment measurements shall not be incorporated in the size designation but, where considered of value, garment measurements may be indicated separately (see 7.3).

6. Size code

The size code, as detailed in table 1, shall be incorporated in the garment label. Examples of how the size code number may be included in the label are given in figure 1.

Table 1. Size codes and associated body measurements

Size codes	Body measurements			
	Hips from	to	Bust from	to
	cm	cm	cm	cm
8	83	87	78	82
10	87	91	82	86
12	91	95	86	90
14	95	99	90	94
16	100	104	95	99
18	105	109	100	104
20	110	114	105	109
22	115	119	110	114
24	120	124	115	119
26	125	129	120	124
28	130	134	125	129
30	135	139	130	134
32	140	144	135	139

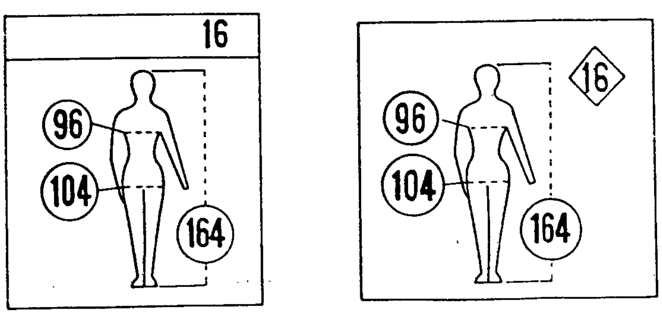
7. Labelling

7.1 Method. The size code and designation of each garment shall be indicated clearly, conspicuously and in a plainly legible form on a label, or on a swing ticket, or on both. Pictograms shall be large enough to ensure immediate understanding and numerals shall, in all cases, be readily discernible.

7.2 Attachment. The label or swing ticket shall be capable of being securely attached to the garment and so positioned as to be easily readable.

7.3 Additional information. Information additional to the size designation may be separately indicated on the label, or on the swing ticket, or on both, provided that it does not in any way reduce the prominence and conspicuousness of the size designation. Such additional information may include a size code number, body measurements or garment measurements considered to constitute useful information.

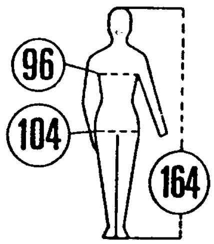
7.4 Examples of labels. The examples of labels given in figures 2 and 3 illustrate methods of labelling that range from the simple indication on the standard pictogram of the relevant control dimensions to more elaborate forms that provide additional information such as a garment dimension or a size code number. Figure 1 gives examples of how to incorporate the size code number into the size label.



SIZE	16
BUST GIRTH	96
HIP GIRTH	104
HEIGHT	164

Figure 1. Examples of inclusion of size code number into label

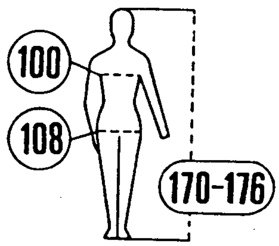
a) Woman's jacket



or

BUST GIRTH	96
HIP GIRTH	104
HEIGHT	164

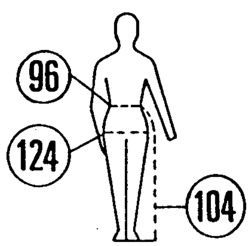
b) Woman's coat or dress



or

BUST GIRTH	100
HIP GIRTH	108
HEIGHT	170 – 176

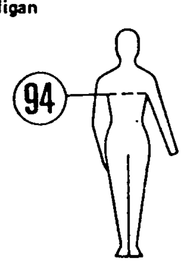
c) Woman's slacks



or

HIP GIRTH	124
WAIST GIRTH	96
OUTSIDE LEG LENGTH	104

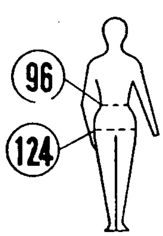
d) Woman's cardigan



or

BUST GIRTH	94

e) Woman's skirt



or

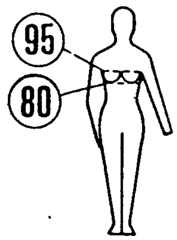
HIP GIRTH	124
WAIST GIRTH	96
SKIRT LENGTH	66 *

NOTE. Examples of how to incorporate the national size code number are given in figure 1.

Figure 2. Examples of labels for women's outerwear

*Example of additional information included in accordance with 7.3.

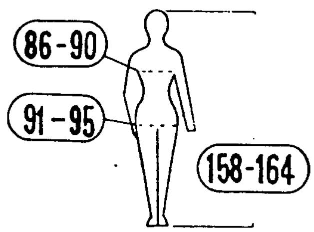
a) Woman's brassiere



or

UNDERBUST GIRTH	80
BUST GIRTH	95

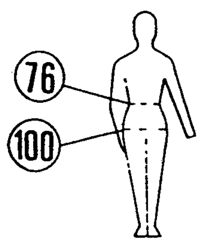
b) Woman's pyjamas



or

BUST GIRTH	86-90
HIP GIRTH	91-95
HEIGHT	158-164

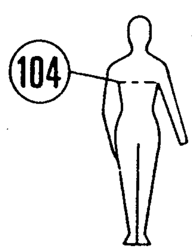
c) Woman's girdle



or

WAIST GIRTH	76
HIP GIRTH	100

d) Woman's sports shirt



or

BUST GIRTH	104

NOTE. Examples of how to incorporate the national size code number are given in figure 1.

Figure 3. Examples of labels for women's underwear

Appendix A

Examples of garments

A.1 Outerwear

A.1.1 *Garments covering the upper or the whole body*

(a) coats, topcoats, raincoats
(b) jackets, blazers, tunics, anoraks
(c) dresses
(d) suits and costumes (2-and 3-piece)
(e) dressing gowns and housecoats
(f) overalls, dustcoats
(g) knitwear (pullovers, cardigans, sweaters)
(h) swimwear
(i) catsuits.

A.1.2 *Garments covering the lower body only*

(a) skirts
(b) trousers, slacks, riding breeches, salopettes
(c) shorts.

A.2 Underwear

A.2.1 *Garments covering the upper body only*

(a) shirts, blouses
(b) vests
(c) foundation garments (brassieres).

A.2.2 *Garments covering the whole body*

(a) body suits, gym suits
(b) slips
(c) foundation garments (corselets)
(d) nightwear (nightdresses, sleepsuits, pyjamas).

A.2.3 *Garments covering the lower body only*

(a) knickers, panties, briefs
(b) half slips
(c) foundation garments (corsets, girdles, pantie girdles).

RELEVANT GRADING TERMINOLOGY

1 Suppression grading
2 Three-dimensional grading
3 Two-dimensional grading
4 Cardinal points
5 Balance
6 Nested (stacked) grading

SUPPRESSION GRADING

This term is applied when the amount of suppression in a pattern is increased or decreased. Suppression is, 'all forms of darts, seams, pleats and gathers which are used to control shape or contour'. It has nothing to do with styling. To suppress is to reduce a girth measurement in relation to another adjacent girth measurement.

THREE-DIMENSIONAL GRADING

This term applies to grading techniques which change suppression as well as girth and height grades.

TWO-DIMENSIONAL GRADING

When the pattern changes only in girth and height and not in shape it is termed two-dimensional. This type of grade is invariably a simplified grade and is initially easier to learn and apply.

CARDINAL POINTS

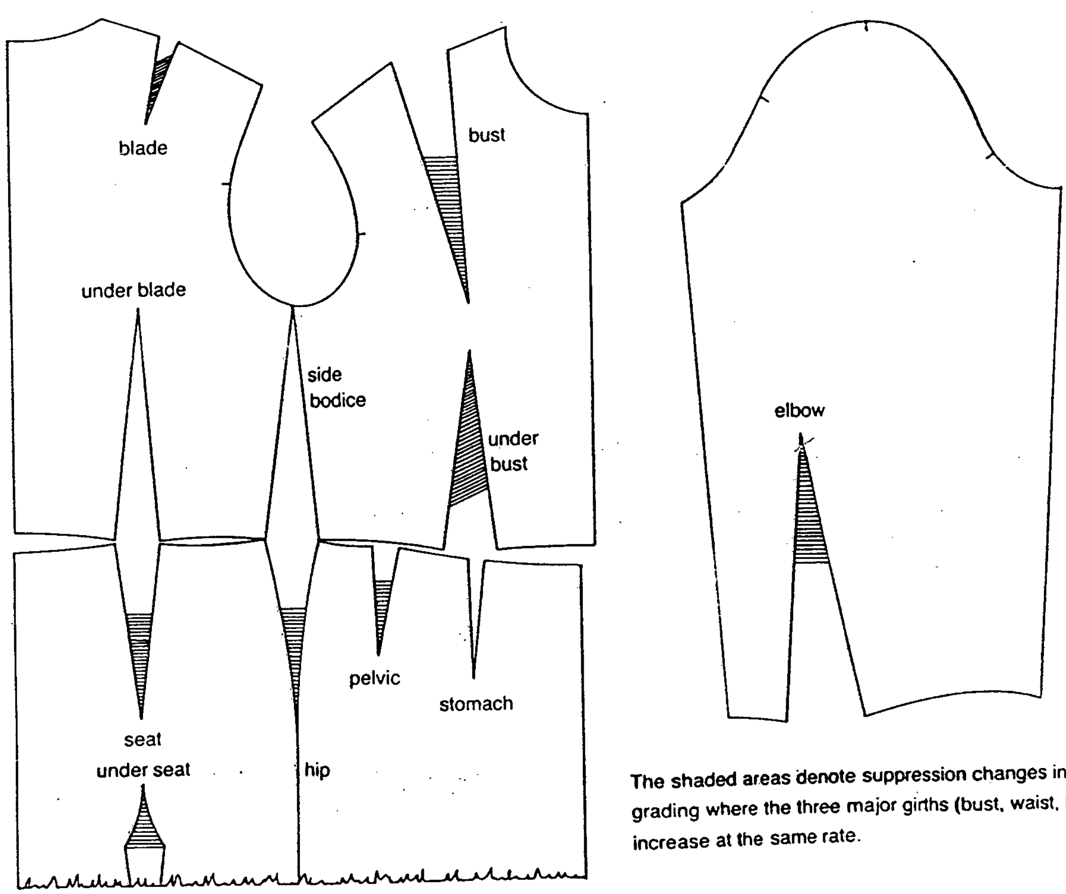
These are the points on the pattern to which grading increments are applied.

BALANCE

There are various interpretations of balance, but for the purposes of this book it refers to the relationship between the front length from nape over bust to waist and floor, and back length from nape to centre back waist to floor. It is also used as a general description, as the word suggests, for a lack of distortion.

NESTED (STACKED) GRADING

This describes the superimposing of one size or another so that the progression of increase is clearly visible.



The shaded areas denote suppression changes in a grading where the three major girths (bust, waist, hip) increase at the same rate.

Figure 3 Main suppression areas

Axiomatic Design

Martin G. Helander
School of Mechanical & Production Engineering
Nanyang Technological University
Singapore

Goal of Axiomatic Design

- The primary goal of Axiomatic Design is to establish a systematic foundation for design activity by two fundamental axioms and a set of implementation methods (Suh, 1990). The axioms are:
  - » Axiom 1: *The Independence Axiom*: Maintain the independence of functional requirements.
  - » Axiom 2: *The Information Axiom*: Minimize the information content in design.

- The first axiom advocates that DPs should be chosen so that each
  $\{FR\} = [A]\{DP\}$ (1)
- FR is satisfied by only one DP. Thus the number of FRs and DPs are equal.
- The best design has a strict one-to-one relationship between FRs and DPs. It is called an uncoupled design.
- This mapping between FRs and DPs is represented by a design equation:

where

- {*FR*} is a column vector that contains all the FRs of the design,
- {*DP*} is a column vector that contains all the DPs of the design, and
- [*A*] is the "design matrix" that defines the relationships between the design parameters and the functional requirements.
- With an equal number (*n*) of FRs and DPs, [*A*] is a square matrix of size *n* x *n*, which measures the effect of *DPj* on *FRi*.
- If a DP influences a FR, this element is non-zero.
- The independence axiom is satisfied for an uncoupled design matrix [*A*] having all non-zero elements on its diagonal, indicating that the FRs are completely independent.

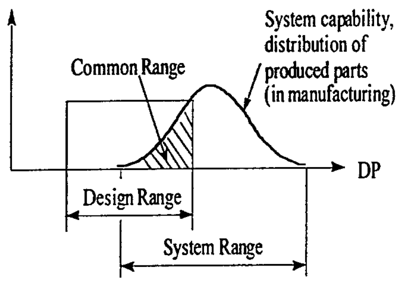
- Designs where FRs are satisfied by more than one DP are acceptable, as long as the design matrix [*A*] is a triangular, that is, the non-zero elements occur in a triangular pattern either about or below the diagonal.
  - » This is called a decoupled design.
- Any other formation of the design matrix that cannot be transformed into a triangular one represents a coupled design, indicating the dependence of the FRs. This design is unacceptable, according to Axiomatic Design.

Information Axiom

- *The Information Axiom* provides a means of selecting among several available design alternatives.
- Select the design with least information.
- Information content is defined in terms of entropy, which is expressed as the logarithm of the inverse of the probability of success *p*:

  I = log 1/p
- In the simple case of uniform probability distribution, the above equation can be written as:

  I = log (System Range/Common Range)



FRs and DPs for design of a driver's compartment. First iteration.

FR1	Easy to Manipulate Controls	DP 1	Controls within Easy Reach
FR 2	Comfortable Sitting	DP2	Ergonomics Design
FR 11	Reach Dashboard Controls	DP 11	Dashboard Close
FR 12	Reach Pedals	DP 12	Long/Short Pedals
FR 21	Clear Steering Wheel	DP 21	Push/Pull Steering Wheel
FR 22	Reach Floor (with feet)	DP 22	Up/Down Seat Height
FR 23	Clear Roof	DP 23	Up/Down Roof
FR 24	Comfortable Sitting	DP 24	Adjustable Backrest Angle

We may then derive the design equation as follows:

$$
\begin{vmatrix} FR_{11} \\ FR_{12} \\ FR_{21} \\ FR_{22} \\ FR_{23} \\ FR_{24} \end{vmatrix}
=
\begin{vmatrix}
A_{111} & 0 & A_{113} & 0 & 0 & 0 \\
0 & A_{122} & 0 & 0 & 0 & A_{126} \\
0 & 0 & A_{212} & 0 & 0 & A_{216} \\
0 & 0 & 0 & A_{224} & 0 & 0 \\
0 & 0 & 0 & A_{234} & A_{235} & 0 \\
0 & 0 & 0 & 0 & 0 & A_{246}
\end{vmatrix}
\begin{vmatrix} DP_{11} \\ DP_{12} \\ DP_{21} \\ DP_{22} \\ DP_{23} \\ DP_{24} \end{vmatrix}
$$

Sequence of setting adjustabilities

- This is a de-coupled design, and acceptable.
- For the operator it is however difficult to learn to operate the different adjustabilities in a specific order.
- In this case DP22 and DP 24 must be dealt with first, followed by the other adjustments.
- Assume a driver will first adjust the Backrest Angle (DP24) considering Comfort.
- He can then set the chair height (DP22) to reach the floor and then push the steering wheel back to accommodate his large stomach.
- He can then consider either of DP 12, DP 21 and DP 23. DP 12 satisfies the reach requirements to the pedals. DP 21 is to fit a large stomach between the steering wheel and DP 23 is to clear the roof.
- Finally the driver can set DP11, the distance to the dashboard.

- The Adjustable Roof and the adjustable Length Pedals are unconventional design solutions, and for the next exploration a more conventional design was chosen: High Roof and Adjustable Seat Forward/Backward.
- The following solution is obtained, see Table 2.

Table 2. FRs and DPs for design of a driver's compartment. Second Iteration.

FR1 Handle Controls	DP 1 Controls within Reach
FR 2 Comfortable Sitting	DP2 Ergonomics Design
FR 11 Reach Dashboard Controls	DP 11 Dashboard Close
FR 12 Reach Pedals	DP 12 Forward/Backward Seat
FR 21 Clear Steering Wheel	DP 21 Push/Pull Steering Wheel
FR 22 Reach Floor (with feet)	DP 22 Up/Down Seat Height
FR 23 Clear Roof	DP 23 High Roof
FR 24 Comfortable Sitting	DP 24 Adjust. Backrest Angle

$$\begin{vmatrix} FR_{11} \\ FR_{12} \\ FR_{21} \\ FR_{22} \\ FR_{23} \\ FR_{24} \end{vmatrix} = \begin{vmatrix} A_{111} & 0 & A_{113} & A_{114} & 0 & 0 \\ A_{121} & A_{122} & A_{123} & 0 & 0 & A_{126} \\ A_{211} & 0 & A_{213} & 0 & 0 & A_{216} \\ 0 & 0 & 0 & A_{224} & 0 & 0 \\ 0 & 0 & 0 & A_{234} & A_{235} & 0 \\ 0 & 0 & 0 & 0 & 0 & A_{246} \end{vmatrix} \begin{vmatrix} DP_{11} \\ DP_{12} \\ DP_{21} \\ DP_{22} \\ DP_{23} \\ DP_{24} \end{vmatrix}$$

Coupled Design

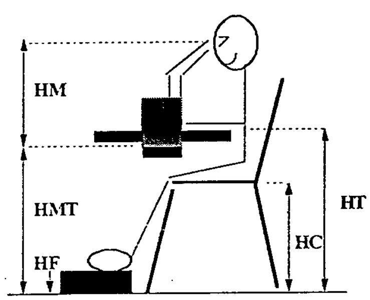
- This is a coupled design, and therefore not satisfactory.
- The driver can first set DP 22 and DP 24, which are independent. DP 23 is then feasible to adjust.
- However, DP 11, DP12 and DP 21 are coupled, which makes it difficult to make the adjustments so as to reach the floor, reach the dashboard and clear the steering wheel.
- Obviously the previous design solution: Long/Short Pedals produced a more satisfactory design than Forward/Backward Seat.
- The latter design, although it is the conventional design found in all cars, creates unwanted couplings, which may be difficult to deal with for the user.

- The design matrix provides a conceptualization of dependencies in design that we would otherwise not have been able to consider.
- Guided by the results of this example we may suggest an uncoupled design, but it is unconventional:
  - Dashboard controls on steering wheel (DP11), Adjustable length pedals (DP12), Push/pull steering wheel (DP21), Height adjustable floor (DP22), High Roof (DP23) and Adjustable backrest angle (DP24).
- Note that in this design Car adjustments are used, and not Seat adjustments.

Microscope Workstation Design

Several adjustability design parameters in a microscope workstation affect operator comfort.

- The height of the table (HT) where the operator is sitting.
- The height of a special microscope table (HMT), which is additional to the worktable
- The height of the microscope eyepieces (HM)
- The height of the operator's chair (HC)
- The height of the foot rest (HF)



First Iteration- Conventional Design

FR = Provide a good work posture

DP = Provide height adjustable workstation

Decompose the top-level FR (good work posture for operators) into the following FRs:

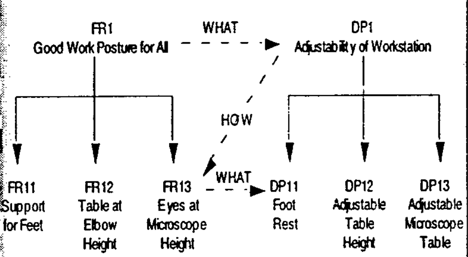
- FR1 = Support for feet
- FR2 = Table top at sitting elbow height
- FR3 = Eyes at microscope height

- DP1 = Adjustable chair height
- DP2 = Adjustable table height
- DP3 = Adjustable microscope height

$$\begin{matrix} FR_1 \\ FR_2 \\ FR_3 \end{matrix} = \begin{matrix} A_{11} & 0 & 0 \\ A_{21} & A_{22} & 0 \\ A_{31} & A_{32} & A_{33} \end{matrix} \begin{matrix} DP_1 \\ DP_2 \\ DP_3 \end{matrix}$$

Decoupled solution - needs to be memorized

- Although this decoupled design is acceptable, a close examination indicates that the operator is required to remember the sequence of adjustments.
- In this case, the chair height needs to be adjusted first, then the table height, and finally the microscope height.
- If this sequence is not followed, repeated iterative adjustments will be necessary. Even though this decoupled design is good enough for axiomatics, it is not good enough for ergonomics, since it would be necessary to train the operator.



$$
\begin{array}{l}
FR_1 \\
FR_2 \\
FR_3
\end{array}
=
\begin{array}{cccc}
A_{11}' & 0 & 0 & DP_1' \\
0 & A_{22}' & 0 & DP_2' \\
0 & A_{32}' & A_{33}' & DP_3'
\end{array}
$$

Last iteration

DP1" = Adjustable footrest
DP2" = Adjustable table height
DP3"= Separate adjustable microscope table

Uncoupled Design. This is the <u>best</u> solution of all the ones proposed. It is however very unconventional, since it does not use a height adjustable chair.

$$
\begin{array}{l}
FR_1 \\
FR_2 \\
FR_3
\end{array}
=
\begin{array}{cccc}
A_{11}'' & 0 & 0 & DP_1'' \\
0 & A_{22}'' & 0 & DP_2'' \\
0 & 0 & A_{33}'' & DP_3''
\end{array}
$$

Desired Range and Supplied Range

- The *Desired Range* is the range implied by a functional requirement (FR). In our case a desired range was set by the 5th-95th percentile anthropometric measures. Thus, for an adjustable table the desired range is 20-29 in., see Table 3.
- The ***Supplied Range*** is the range supplied by the manufacturer.
- The **Common Range** then is the common area for the two distributions (overlap of Supplied Range and Desired Range).

Calculation of Information in Adjustability

Here the probability of success is:

p = Common Range/Desired Range.

As with Axiomatic Design the definition for information content is:

I = log2 (1/p). Thus, the information content is redefined as:

I = log2 (Desired Range/Common Range).

Table 3. Information Content of Two Adjustable Microscope Workstations

		Manuf. A		Manuf. B	
	Desired Range	Suppl. Range	Info. (bit)	Suppl. Range	Info. (bit)
Adjustable Footrest	0 - 5	3 - 6	1.32	2 -5	0.74
Adjustable Table	20 - 29	23 - 32	0.58	21 - 27	0.58
Microscope Table	20 -25	23 - 28	1.32	21 - 27	0.32
Total Info			3.22 bits		1.64 bits

Discussion

- The Effect of FRs and DPs
- Focus on the goals for design
- Sequence of Adjustability
- Unconventional Design Solutions
- Information in Design

ANTHROPOMETRIC DESIGN OF WORKSTATIONS

Martin G. Helander
School of Mechanical and Production Engineering
Nanyang Technological University
Singapore 639798

Li Lin
Department of Industrial Engineering
State University of New York at Buffalo
Buffalo, NY 14260, USA

ABSTRACT

In this study, the use of AD was demonstrated for anthropometric design of workplaces. Two examples explore how the formulation of Functional Requirements and Design Parameters can help in conceptualizing design principles and selecting design parameters at a seated work place. To improve the ease of adjustability the *Independence Axiom* was used to formulate functional requirements with respect to adjustability, and select suitable design parameters. *The Information Axiom* was then used to calculate the information in adjustability features. This involved a redefinition of the concepts of system range and design range, which are used in AD, and resulted in a modified calculation of information contents. The two axioms in Axiomatic Design (AD) fit well with ergonomics: 1. Formulations of functional requirements are essential to ergonomics design, since they drive design solutions. 2. Minimization of information in ergonomics in an operator interface will simplify the operation of the interface. The less the information the quicker it is to operate and the easier it is to learn.
Keywords: anthropometry, workstation design, Fitts' law, Hick's law

1 INTRODUCTION

The primary goal of Axiomatic Design is to establish a systematic foundation for design activity by two fundamental axioms and a set of implementation methods (Suh, 1990). The axioms are:

Axiom 1: *The Independence Axiom*: Maintain the independ-ence of functional requirements.

Axiom 2: *The Information Axiom*: Minimize the informat-ion content in design.

The first axiom advocates that for a good design, the DPs should be chosen so that each FR is satisfied by only one DP. Thus the number of FRs and DPs is equal. The best design has a strict one-to-one relationship between FRs and DPs. It is called an uncoupled design. This mapping between FRs and DPs is represented by a design equation:

$$\{\boldsymbol{FR}\} = [A]\,\{\boldsymbol{DP}\} \qquad (1)$$

where $\{\boldsymbol{FR}\}$ is a column vector that contains all the FRs of the design,
$\{\boldsymbol{DP}\}$ is a column vector that contains all the DPs of the design, and
$[A]$ is the "design matrix" that defines the relationships between the design parameters and the functional requirements.

With an equal number (n) of FRs and DPs, $[A]$ is a square matrix of size n x n, which measures the effect of DP_j on FR_i. If the DP influences the FR, this element is non-zero. Otherwise it is zero. The independence axiom is satisfied for an uncoupled design matrix $[A]$ having all non-zero elements on its diagonal, indicating that the FRs are completely independent. However, complete uncoupling may not be easy to accomplish in a complex real world, where interactions of factors are common. Designs where FRs are satisfied by more than one DP are acceptable, as long as the design matrix $[A]$ is a triangular, that is, the non-zero elements occur in a triangular pattern either about or below the diagonal. This is called a decoupled design. A decoupled design still satisfies the independence axiom, provided that the DPs are specified in a

sequence such that each FR is ultimately controlled by one unique DP. Any other formation of the design matrix that cannot be transformed into triangular one represents a coupled design, indicating the dependence of the FRs. Therefore, the design is unacceptable, according to Axiomatic Design.

The Information Axiom provides a means of evaluating the quality of designs, thus facilitating a selection among available design alternatives. This is accomplished by comparing the information content of the several designs in terms of their respective probabilities of successfully satisfying the FRs. Information content is defined in terms of entropy, which is expressed as the logarithm of the inverse of the probability of success p:

$$I = \log_2 \frac{1}{p} \tag{2}$$

In the simple case of uniform probability distribution, the above equation can be written as:

$$I = \log_2 (\text{System Range}/\text{Common Range}) \tag{3}$$

where, System Range is the capability of the current system, given in terms of tolerances, Common Range refers to the amount of overlap between the Design Range and the system capability, and Design Range is the acceptable range associated with the DP specified by the designer, see Figure 1.

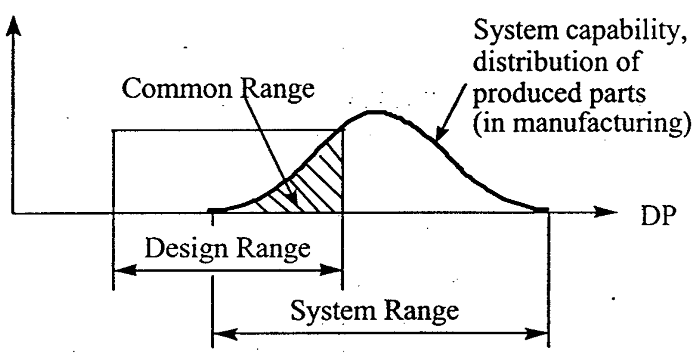


Figure 1: Definition of Design Range, System Range and Common Range for the Calculation of Information Content

By definition, the total information of a design for n FRs is given by the sum of the information content calculated for each FR, including any conditional probabilities: All alternative designs are compared by their total information content; and the design chosen is the one with the minimum amount of information. Below we provide two examples of axiomatic design for design of sitting workplaces.

2 ERGONOMICS DESIGN

In anthropometry human body dimensions are used to design artifacts. The general principle is that the artifact must fit the size of the human body (Helander, 1995). But operators or users vary in size. Percentiles of body measures are commonly used to represent variability - from 5^{th} percentile small size to 95^{th} percentile large size. Several different body measures are used for design purposes, such as stature, sitting eye height, sitting elbow height, forward reach, lower leg length, and so forth. These measures are listed in anthropometric tables for various populations – civilians, men/women, U.S. Air Force pilots, and so forth. It would be too expensive to design for dwarfs and giants, therefore the 5^{th} to 95 th range is commonly used for design. There are many

anthropometric design guidelines and they are commonly used for design of airplane cockpits, automobile compartments, chairs and workplace arrangements (Helander, 1995).

2.1 Design of adjustability in a driver's compartment

To design a driver's compartment reach distances are usually dimensioned for 5th percentile small user (large persons can overreach) and clearance dimensions for 95th percentiles large users (small persons can always fit). Figure 1 illustrates several possible design parameters. There is a choice between a. *Seat adjustments* that puts the driver's seat in an advantageous position and b. *Car adjustments* that make the car adjust to the person. An example of the latter is a steering wheel that can be pulled out or pushed in. For a design of a driver's compartment the top-level FR1 and FR2 and the corresponding DP1 and DP2 are given in Table 1.

Table 1. FRs and DPs for design of a driver's compartment. First iteration.

FR1	Easy to Manipulate Controls	DP 1	Controls within Easy Reach
FR 2	Comfortable Sitting	DP2	Ergonomics Design
FR 11	Reach Dashboard Controls	DP 11	Dashboard Close
FR 12	Reach Pedals	DP 12	Long/Short Pedals
FR 21	Clear Steering Wheel	DP 21	Push/Pull Steering Wheel
FR 22	Reach Floor (with feet)	DP 22	Up/Down Seat Height
FR 23	Clear Roof	DP 23	Up/Down Roof
FR 24	Comfortable Sitting	DP 24	Adjustable Backrest Angle

The top level FRs and DPs are then decomposed and their constraining influences are used to derive FRs and suggest DPs at a lower level of abstraction: Given the top goal FR 1 - to make it easy to manipulate controls, and given that we have decided to put controls within easy reach (DP 1), we may then proceed to formulate FR11 and FR12 at a lower level of abstraction and select DP 11 and DP 12, see Table 1. We may then derive the design equation as follows:

$$\begin{vmatrix} FR_{11} \\ FR_{12} \\ FR_{21} \\ FR_{22} \\ FR_{23} \\ FR_{24} \end{vmatrix} = \begin{vmatrix} A_{111} & 0 & A_{113} & 0 & 0 & 0 \\ 0 & A_{122} & 0 & 0 & 0 & A_{126} \\ 0 & 0 & A_{212} & 0 & 0 & A_{216} \\ 0 & 0 & 0 & A_{224} & 0 & 0 \\ 0 & 0 & 0 & A_{234} & A_{235} & 0 \\ 0 & 0 & 0 & 0 & 0 & A_{246} \end{vmatrix} \cdot \begin{vmatrix} DP_{11} \\ DP_{12} \\ DP_{21} \\ DP_{22} \\ DP_{23} \\ DP_{24} \end{vmatrix}$$

This is a de-coupled design, and therefore acceptable. For the operator it is however difficult to learn to operate the different adjustabilities in a specific order (see also example 2 below). In this case DP22 and DP 24 must be dealt with first, followed by the other adjustments. Assume a driver will first adjust the Backrest Angle (DP24) considering Comfort. He can then set the chair height (DP22) to reach the floor and then push the steering wheel back to accommodate his large stomach. He can then consider either of DP 12, DP 21 and DP 23. DP 12 satisfies the reach requirements to the pedals. DP 21 is to fit a large stomach between the steering wheel and DP 23 is to clear the roof. Finally the driver can set DP11, the distance to the dashboard.

The design matrix represents a simplified representation of user requirements. FR 24 - Comfortable Sitting, is assumed to be accomplished by a single design parameter, DP 24 – Adjustable Backrest Angle. From a biomechanics perspective this is indeed the most important variable, since a large hip joint angle has reduces the compressive force in the spine (Helander, 1995). We could also have considered additional design parameters, such as Adjustable Length Seat Pan. Fifth percentile users need a short Seat Pan to reach to the backrest with their back, whereas 95th percentile users need a long Seat Pan to support their thighs. An Adjustable Seat Pan

would also affect some of the other FRs. Although this design solution was not explored here, it would be worthwhile to consider this and other design parameters.

One might argue that The Adjustable Roof and the adjustable Length Pedals are unconventional design solutions, and for the next exploration a more conventional design was chosen: High Roof and Adjustable Seat Forward/Backward. The following solution is obtained see Table 2.

Table 2. FRs and DPs for design of a driver's compartment. Second Iteration.

FR 1	Handle Controls	DP 1	Controls within Reach
FR 2	Comfortable Sitting	DP2	Ergonomics Design
FR 11	Reach Dashboard Controls	DP 11	Dashboard Close
FR 12	Reach Pedals	DP 12	Forward/Backward Seat
FR 21	Clear Steering Wheel	DP 21	Push/Pull Steering Wheel
FR 22	Reach Floor (with feet)	DP 22	Up/Down Seat Height
FR 23	Clear Roof	DP 23	High Roof
FR 24	Comfortable Sitting	DP 24	Adjustable Backrest Angle

$$\begin{vmatrix} FR_{11} \\ FR_{12} \\ FR_{21} \\ FR_{22} \\ FR_{23} \\ FR_{24} \end{vmatrix} = \begin{vmatrix} A_{111} & 0 & A_{113} & A_{114} & 0 & 0 \\ A_{121} & A_{122} & A_{123} & 0 & 0 & A_{126} \\ A_{211} & 0 & A_{213} & 0 & 0 & A_{216} \\ 0 & 0 & 0 & A_{224} & 0 & 0 \\ 0 & 0 & 0 & A_{234} & A_{235} & 0 \\ 0 & 0 & 0 & 0 & 0 & A_{246} \end{vmatrix} \begin{vmatrix} DP_{11} \\ DP_{12} \\ DP_{21} \\ DP_{22} \\ DP_{23} \\ DP_{24} \end{vmatrix}$$

This is a coupled design, and it is therefore not a satisfactory solution. The driver can first set DP 22 and DP 24, which are independent. DP 23 is then feasible to adjust. However, DP 11, DP12 and DEP 21 are coupled, which makes it difficult to make the adjustments so as to reach the floor, reach the dashboard and clear the steering wheel. Obviously the previous design solution: Long/Short Pedals produced a more satisfactory design than Forward/Backward Seat. The latter design, although it is the conventional design found in all cars, creates unwanted couplings, which may be difficult to deal with for the user.

To summarize, this exercise demonstrates the use of AD for anthropometric design. The design matrix provides a conceptualization of dependencies in design that we would otherwise not have been able to consider. Guided by the results of this example we may suggest an uncoupled design, but it is unconventional: Dashboard controls on steering wheel (DP11), Adjustible length pedals (DP12), Push/pull steering wheel (DP21), Height adjustable floor (DP22), High Roof (DP23) and Adjustable backrest angle (DP24). Note that in this design the Car adjustments are used, and not seat adjustments.

Below we offer a second example of anthropometrics design – for microscope workstations.

2.2 Anthropometric design of microscope workstation.

A study was performed at IBM Corporation in San Jose with the purpose of developing guidelines for anthropometric design of microscope workplaces (Helander, Grossmith, and Prabhu [3]). Microscope work is generally taxing, since the operators have to assume a very static work posture – the eyes must constantly be positioned at the eyepiece and the hands on the focus controls. At IBM Corporation in San Jose, there were about 1000 microscope operators, most of whom were Asian females. They were much smaller than the regular USA population. As a result many of them could not accommodate to the oversize work place. The seat pan of the chair was too long so that they could not use the backrest. The seat was too high so that their feet could not reach the

floor. The eyepieces were too high so that the operators had difficulties looking through them and seeing the magnified items.

To understand the underlying design problem an anthropometric survey was conducted. Fifteen different body measures were recorded for 400 operators and 5 th percentile (5 % smallest), 50th percentile (average) and 95th percentile (5 percent largest) were calculated.

In our report we recommended a conventional design solution using a height adjustable chair, a height adjustable table and a height adjustable microscope (Helander, Grossmith, and Prabhu [3]) The amount of height adjustability was determined so as to fit a design range of 5th through 95th percentile operators. The use of height adjustable chairs is a conventional design recommendation and is without exception recommended in the literature [e.g. 4,5]. As we will see below the height adjustable chair is not necessary. It is possible to use Axiomatic Design to derive a better, albeit unconventional design solution

General analysis of the design. In the daily work situation, a microscope operator must make the necessary adjustments so that the workstation is comfortable. There are several possible adjustability design parameters in a microscope workstation that may affect operator comfort, see Figure 1 [6]. Hardware manufacturers can supply all these height adjustabilities, including the microscope itself:

- The height of the table (HT) where the operator is sitting.
- The height of a special microscope table (HMT), which is additional to the worktable
- The height of the microscope eyepieces (HM)
- The height of the operator's chair (HC)
- • he height of the foot rest (HF)

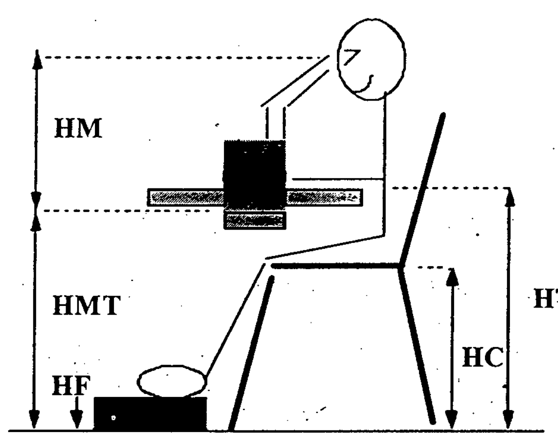


Figure 1: Design of a Microscope Workstation

We can now specify the top-level FR and its corresponding DP:

FR = Provide a good work posture for operators at a microscope workstation

DP = Provide height adjustable workstation

A further analysis based on the decision of using ergonomic design in an adjustable workstation decomposed the top-level FR (good work posture for operators) into the following FRs:

FR_1 = Support for feet

FR_2 = Table top at sitting elbow height

FR_3 = Eyes at microscope height

These FRs are reasonable, and they are commonly recommended, since they avoid many potential biomechanics problems. The top-level DP was decomposed using the conventional solution that was proposed to IBM in our study [3].

DP_1 = Adjustable chair height
DP_2 = Adjustable table height
DP_3 = Adjustable microscope height

Analysis of ind.:pendence of the design: The design equation is given as

$$\begin{bmatrix} FR_1 \\ FR_2 \\ FR_3 \end{bmatrix} = \begin{bmatrix} A_{11} & 0 & 0 \\ A_{21} & A_{22} & 0 \\ A_{31} & A_{32} & A_{33} \end{bmatrix} \begin{bmatrix} DP_1 \\ DP_2 \\ DP_3 \end{bmatrix}$$

Although this decoupled design is acceptable in the conventional sense of Axiomatic Design, a close examination indicates that the operator is required to remember the sequence of adjustments to bring about the best sitting posture. In this case, the chair height needs to be adjusted first, then the table height, and finally the microscope height. If this sequence is not followed, repeated iterative adjustments will be necessary. Even though this decoupled design is good enough for axiomatics it is not good enough for ergonomics, since it would be necessary to train the operator.

Reducing coupling in design. To improve the usability, and thus the design itself, other design solutions were tried. An adjustable footrest could be used instead of a height adjustable chair to satisfy FR_1 (Support for feet), and DP_1 was changed:

DP_1' = Adjustable footrest
DP_2' = Adjustable table height
DP_3' =Adjustable microscope height

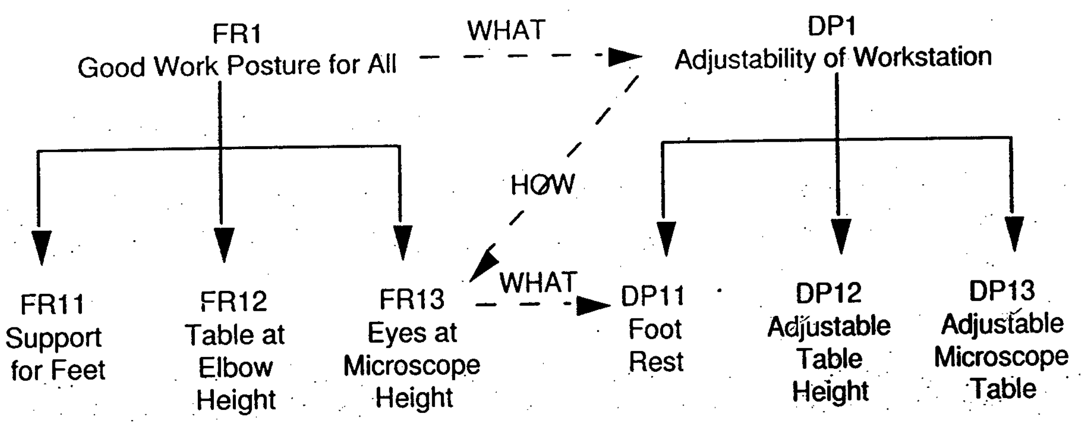


Figure 2: Hierarchical Structures and Decomposition of FRs and DPs. Note the zigzagging

The resultant design equation, with the modified design matrix $[A']$, is:

$$\begin{bmatrix} FR_1 \\ FR_2 \\ FR_3 \end{bmatrix} = \begin{bmatrix} A_{11}' & 0 & 0 \\ 0 & A_{22}' & 0 \\ 0 & A_{32}' & A_{33}' \end{bmatrix} \begin{bmatrix} DP_1' \\ DP_2' \\ DP_3' \end{bmatrix}$$

This improved solution uses an independently adjustable footrest, which replaces the adjustable chair in satisfying FR_1 (Support for feet). Obviously a non-adjustable chair is then necessary, and it should be sufficiently high to accommodate tall operators.

Since the coupling is reduced this is a better design solution. The operator will still, however, be forced to set the adjustabilities in a certain sequence. DP_2' (Adjustable table height) must be set before DP_3' (Adjustable microscope height) otherwise repeated adjustments will be necessary. (This is simply due to the fact that the microscope is placed on the worktable). To further improve the design, we provided a separate adjustable microscope table, standing free from the worktable, see figure 2. Thus the modified DPs are

DP_1'' = Adjustable footrest
DP_2'' = Adjustable table height
DP_3'' = Separate adjustable microscope table

The resultant design equation, with the further modified design matrix $[A'']$ is:

$$\begin{bmatrix} FR_1 \\ FR_2 \\ FR_3 \end{bmatrix} = \begin{bmatrix} A_{11}'' & 0 & 0 \\ 0 & A_{22}'' & 0 \\ 0 & 0 & A_{33}'' \end{bmatrix} \begin{bmatrix} DP_1'' \\ DP_2'' \\ DP_3'' \end{bmatrix}$$

By now we have achieved an uncoupled design that does not require any specified sequence to make the adjustments. Clearly, this is the <u>best</u> solution of all the ones proposed. It is however very unconventional, since it does not use a height adjustable chair. We have not seen this design solution documented in the literature.

Next we will discuss a difficulty encountered in ergonomic design when using the second axiom, *The Information Axiom*.

3. USING THE INFORMATION AXIOM IN ERGONOMICS DESIGN

3.1 Calculating the Information Content

In this section, we will give an example of how to calculate the information content in anthropometric design. As an illustration we use the microscope workstation in the previous example. The ranges of adjustment for the footrest, the table and the separate microscope table are defined based on anthropometric data of the intended user population.

The next step was to buy adjustable furniture that was available on the market. Realistically, the design ranges for adjustability that were offered by furniture manufacturers were unlikely to fit our specific population - small Asian women. Below we demonstrate the use of the *Information Axiom* as a criterion to select the best furniture.

In Axiomatic Design the <u>Design Range</u> is specified as "the tolerance associated with the DP specified by the designer." In our case this <u>could</u> correspond to the desirable ranges of adjustment based on anthropometric measures. The <u>System Range</u> is defined as "the capability of the current (manufacturing) system, given in terms of tolerances". This <u>could</u> correspond to the ranges of adjustment offered by furniture manufacturers. Using these and the <u>Common Range</u> between them, the information content of each set of furniture may be calculated and the one with the least information content may be selected, according to *The Information Axiom*. However, a straightforward application of the AD principles would be misleading. Let us illustrate this with the following example.

Suppose that by surveying a user group, we had determined the desirable adjustable table height ranges from 20-30 inches (Design Range = 10 in.), and there were two tables from two different manufacturers to evaluate. Table A had an adjustable range from 20-25 inches (System Range A = 5 in., and the corresponding Common Range A = 5 in.), and table B had a range from 20-35 inches (System Range B = 15 in., and the corresponding Common Range B = 10 in.). Using Equation (3) and assuming uniform distributions, the information contents of the two tables may then be calculated as:

Table A: $I_A = \log_2$ (System Range A/Common Range A) = $\log_2$ (5/5) = 0
Table B: $I_B = \log_2$ (System Range B/Common Range B) = $\log_2$ (15/10) = 0.58

According to Axiomatic Design, table A would have been selected because it has less information content than table B. However, table B clearly will satisfy the full range of user group while table A covers only half of them, and the correct choice would actually be table B.

This difficulty in calculating the information content, as a criterion for selecting alternative designs, stems from the special concern in ergonomic design, the human user. Once a selection is made, an individual user is merely a sample from the distribution of the user population. In other words, the furniture will be fixed once selected; a random user that follows a distribution of the Design Range would use it. This is contrary to the manufacturing case, where a product follows a distribution of the System Range. Therefore, this unique difficulty is ultimately from the definition of Design Range and System Range. To resolve this, we redefine the ranges to take human users into account.

3.2 Modification to the Calculation of Information Content in Ergonomics Design

We introduced new definitions of the information ranges according to the following notations. The ***Desired Range*** is the range implied by a functional requirement (FR). In our case a desired range was set by the 5th-95th percentile anthropometric measures. Thus, for an adjustable table the desired range is 20-29 in., see Table 3. The ***Supplied Range*** is the range supplied by the manufacturer. The Common Range then is the common area for the two distributions (overlap of Supplied Range and Desired Range). Here the probability of success is: p = Common Range/Desired Range. As with Axiomatic Design the definition for information content is $I = \log_2 (1/p)$. Thus, the information content is redefined as:

$I = \log_2$ (Desired Range/Common Range).

For the table height and manufacturer A, the Supplied Range is 23-32 in. and is calculated as 6 in. Using the simple case of uniform probability distribution, for manufacturer A we obtain:

$I_A = \log_2$ (Desired Range A/Common Range A) = $\log_2$ (9/6) = 0.58 bits.

Design Problem: The next step is to choose the furniture offered by vendors. In our case we made the assumption that different vendors offers different ranges of adjustment, and we need to evaluate each vendor to make a final selection. *The Information Axiom* was used for this purpose, and the design with the minimum amount of information was used.

Design Solution: First the desired ranges were determined using anthropometric data. The desired ranges were: 0-5 inches for the footrest, 20-29 inches for the table, and 20-25 inches for the microscope table. As the two manufacturers, A and B, provided different adjustment ranges, their information contents were calculated using Equation (5), and the results are summarized in Table 3.

Table 3. Information Content of Two Adjustable Microscope Workstations

Info.	Desired Range (in.)	Manufacturer A Supplied Range (in.)	Info. (bit)	Manufacturer B Supplied Range (in.)	Info. (bit)
Adjustable Footrest	0 - 5	3 - 6	1.32	2 -5	0.74
Adjustable Table	20 - 29	23 - 32	0.58	21 - 27	0.58
Microscope Table	20 -25	23 - 28	1.32	21 - 27	0.32
Total Information			3.22		1.64

We conclude that manufacturer A's workstation has total information content of 3.22 bits, and manufacturer B has 1.64 bits. Since there is less information in alternative B, this is a better design.

4 DISCUSSION

4.1 Conceptual support for Design

This paper has illustrated the use of Axiomatic Design in Anthropometric design of workstations. There were two examples, a driver's compartment and a microscope workstation. In the drivers compartment we provided examples of how decoupled design parameters simplify adjustments. It does not seem to be possible to find an uncoupled solution, unless design of vehicles is altered extensively. For example, the controls on the dashboard are in conflict with the steering wheel. An individual with a 5th percentile reach distance and a 95th percentile stomach girth may have difficulties to reach the dashboard controls. We could suggest several design solutions, such as a joystick for steering, putting the dashboard controls on the steering wheel, and so forth. However, they would violate existing design standards, and are therefore not so practical.

It would have been informative to explore how design parameters affect the extremes of the driver population. Usually the average driver has no problems, but the 5th and the 95th percentile drivers do. However, their problems are different and individual treatments of the 5th and 95 th percentiles may suggest new de-coupled solutions.

The design of the microscope workstation was different in that it was possible to suggest a practical, uncoupled design. BY using the independence axiom we were able to reason about the effect of alternative DPs. An unconventional design solution was accepted: the height adjustable chair was replaced by a footrest and an extra table was for the microscope was positioned inside the regular worktable. We discovered that height adjustable chairs were ineffective, since they impose a predetermined sequence of adjustability corrections that is difficult for the user to learn.

The design equations and some figures in this paper gave examples of the zigzagging between the functional domain and the design domain. The zigzagging procedure has a great advantage in that it can visualize how the choice of FRs and DPs at a high level of abstraction constrains the choice of FRs and DPs at the lower levels of abstraction. The zigzagging therefore introduces a method for constraint propagation, which is useful in delimiting the design space, and helps designers to arrive at reasonable solutions.

4.2 Information in Design

In the calculation of information in adjustability we introduced a new methodology to calculate information that is better suited to ergonomics than the existing methodology. The latter is shown in Figure 1.

"Desired range" and "supplied range" were suggested, and these concepts can then be used for calculating the amount of information in an adjustable workstation. Ideally the information H should be zero, which would indicate that all percentile users can be accommodates by the design.

According to the information axiom, one must minimize the information in a design solution. The principle is well known in ergonomics and has previously been formalized in two laws. These laws are important since they are insofar the only laws that have been formulated in ergonomics:

(1) Hick's law quantifies the information uncertainty H or entropy in a situation [4].

$$H = \Sigma -p_i \log_2 p_i \text{ (bits)}. \qquad (4)$$

where p_i is the probability of using information source I.

It is well established that human reaction time is a linear function of H. The greater the information uncertainty H, the longer the reaction time RT. This is expressed as follows:

$$RT = A + CH \qquad (5)$$

where A and C are constants.

In human factors design it is therefore considered desirable to reduce information in design. For example, the many options displayed in the menu for MSWord increase human

reaction time. It would be better to display only those options that are actually used, and delete routines that are not useful. As an example, Tetra Pak, a Swedish Packaging Company formulated company wide requirement specifications for computer aided design. Based on the identified requirements (FRs), the CAD software packages were modified and all unnecessary functionality was removed. This simplified the operation of CAD routines, and training time as well as operational time decreased.

(2) Fitts' law can be used for calculating the information in a hand movement and the time it takes to perform a movement [1].

$$T = K \log_2 D/W \qquad (6)$$

where T is the time taken for a movement, K is a constant, and D is the distance to a target, and W is the width of the target. D/W expresses the relative precision of a movement.

Fitts' law has been used to model human movement time for a variety of situations, such as movement time for cursor controls in computers, and movement time to pick items from bins in manufacturing, and sorting letters into mail slots. The smaller the size of the target and the longer the movement distance, the longer it takes to complete the movement. This leads to tradeoffs in design. For example, bins for assembly may be located in a semi-circular layout around the operator. The further away they are located, the greater the number of bins can be

The expressions used to calculate information for Hick's law and Fitts' law are computationally identical to those suggested by Suh [2]. To the ergonomics science the information axiom therefore carries much face validity, and it is possible that the information axiom in the future can be formalized in ergonomics design. Further research is necessary. In particular we advocate the use of case studies to further develop an understanding how AD can be used in design. The examples presented in the paper are easy to analyze. It would be particularly interesting to apply AD to real tasks including complex design with a mix of physical (anthropometry) and mental (information processing).

4.3 Process variables.

Process variables (PVs) are a set of variables used to achieve design parameters. Just like DPs are chosen so as to uncouple FRs, PVs should be chosen so that DPs are uncoupled. PVs usually refer to manufacturing machinery and processes. In the case of ergonomics, PVs refer to the functionality or capabilities the perceptual system and information processing, decision making, and the use of muscles to effectuate decisions. In other words, in designing a workstation one should consider human capabilities and limitations such as: information processing, decision making and muscular capability. These PV's can then be related to DP's through quantifications such as Hick's and Fitts' laws. In other words - a set of proposed design parameters can be evaluated in terms of the human processes that are necessitated through the design.

5 CONCLUSION

Axiomatic Design seems to offer a foundation for design methodology in ergonomics. There are several compelling reasons:

(1) Axiomatic Design offers a clear framework for the identification of functional requirements and the corresponding design parameters that may be evaluated with respect to user requirements.
(2) An analysis of the design matrix can reveal independence/dependence of functional requirements and point to possible ways of improving the design.
(3) The calculation of information content provides a quantitative evaluation of alternative designs so the best design can be selected; and
(4) The decomposition through the hierarchical structures of FRs and DPs by the zigzag process offers a procedure to constrain design solutions and at the same time identify critical design parameters.

Further research is now necessary to formalize the use of top-down design procedures in ergonomics. We believe that a top-down procedure, such as AD will have a promising potential in providing guiding principles for ergonomics research in the future.

6 REFERENCES

[1] Helander, M.G., *A Guide to the Ergonomics of Manufacturing*, London: Taylor & Francis, 1995. ISBN 0-7484-0122-9

[2] Suh, N., *The Principles of Design*. New York: Oxford University Press, 1990. ISBN 0-19-504345-6

[3] Helander, M.G., Grossmith, E. & Prabhu, P., "Visual and Postural Ergonomics in Design of Microscope Workplaces", *Applied Ergonomics*, *Vol.* 22, pp.36-42, 1990.

[4] Evans, W.A., Courtney, A.J. & Fok, K.F., "The Design of School Furniture for Hong Kong Schoolchildren", *Applied Ergonomics*, Vol. 19, pp.122-134, 1988.

[5] Verbreek, J., "The Use of Adjustable Furniture: Evaluation of an Instruction Programme for Office Workers", *Applied Ergonomics,* Vol. 22, pp.179-184, 1991.

[6] Helander, M.G., "Conceptualizing the Use of Axiomatic Design Procedures in Ergonomics", *Proc. of IEA World Conference,* pp.38-41. Rio de Janeiro: Associacao Brasileira de Ergonomia, 1995.

[7] Shannon, C.E. And Weaver, W., *The Mathematical Theory of Communication,* Urbana-Champagne, IL: University of Illinois Press, 1949

Chapter 3

Anthropometry in Workstation Design

The basic philosophy of ergonomics is to design workstations that are comfortable, convenient and productive to work at. Ideally, workstations should be designed to fit both the body and the mind of the worker. In this chapter we limit ourselves to the body, which certainly is the easier of the two problems. We will demonstrate how adjustability of chairs, stools, benches, and so forth, can help to accommodate people of different body size. By the use of anthropometric design principles it is possible for a variety of people to find physical comfort at a workstation. On the other hand, by not taking into consideration these physical requirements, one may create bad work postures, which lead to fatigue, loss of productivity and sometimes injury.

Anthropometry is not only a concern about appropriate working height, but also about how the operator can easily access controls and input devices. In an automobile it should be possible for a small driver to reach the controls on the dashboard while being held back by the seatbelt. Similarly, the controls of machine tools must be easy to reach. The lathe shown in Figure 3.1 was originally described by Singleton (1962). It is a classic design and makes a clear argument. To control this particular piece of equipment the ideal operator should be 137 cm (4.5 feet) tall, 62 cm (2 feet) across the shoulders, and have a 235 cm (8 feet) armspan, which is closer to the shape of a gorilla!

3.1 Measuring Human Dimensions

There are large differences in body size due to gender and genetics. Men are, on average, 13 cm (5 in.) taller than women and are larger in most other body measures as well.

Genetic differences are evident from a comparison of individuals living in different countries. For example, the average male stature in the USA is 167 cm (66 in.), whereas that in Vietnam is 152 cm (60 in.). A car designed for the US population would fit only about 10% of Vietnamese, unless of course the differences can be compensated for by using an adjustable seat (Chapanis, 1974). However, some of the differences between countries are decreasing, suggesting that there are factors beyond genetics. For example, during the last 20 years the average Japanese teenager has become 12 cm taller (Pheasant, 1986). This is largely attributed to changes in eating habits; in particular, animal proteins have become much more common in the Japanese diet.

According to a study done in the UK, the average male manager is 3–4 cm taller than the male blue-collar worker (Pheasant, 1986). There could be many reasons for this. It may be that taller people are more often promoted to managers, or that taller people are a little more intelligent, or that managers come from a higher social class and thus had better education and also eat more animal protein. It is difficult

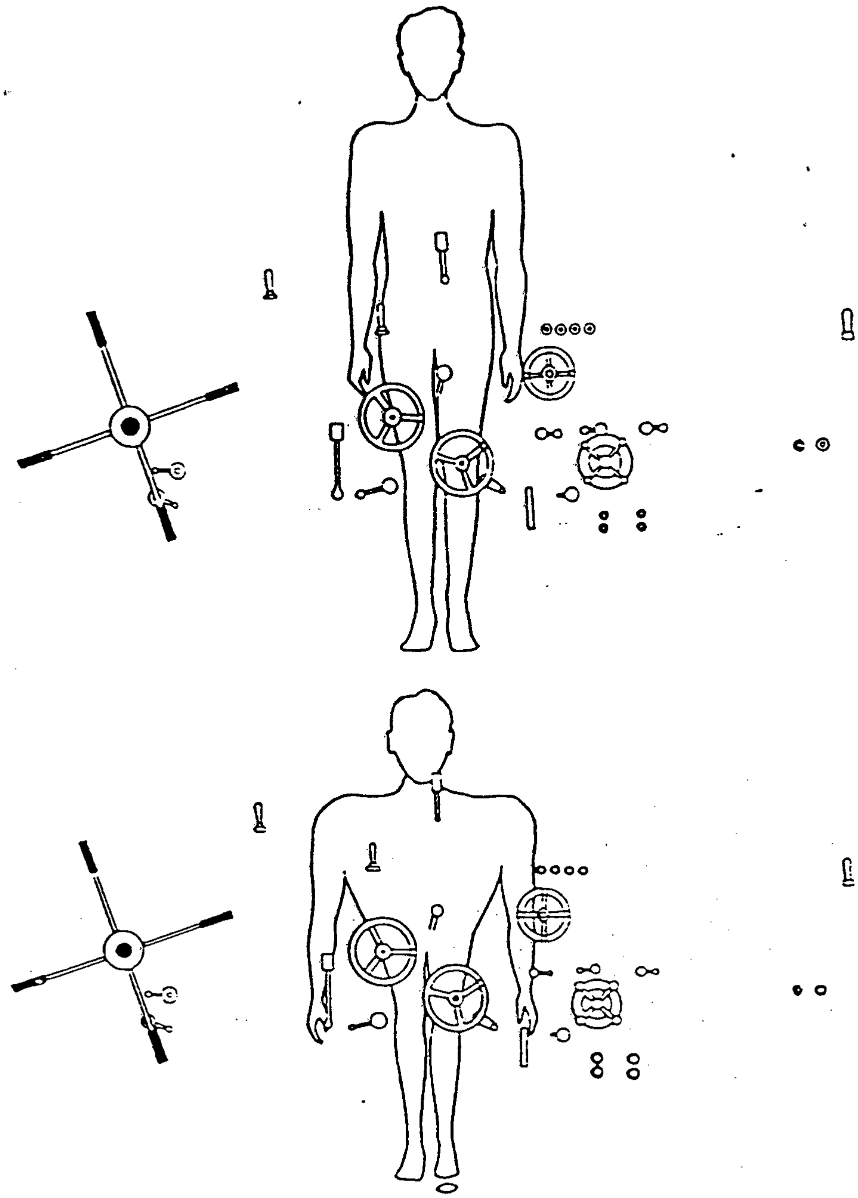


Figure 3.1 The controls of a lathe are not within easy reach of the average man. The bottom figure shows the ideal size operator (Singleton, 1962)

to attribute causes, but probably all of these reasons contribute. Of particular interest to ergonomics is that a male manager may have a different physical frame of reference than the individuals who work for him. For example, a managerial chair is oversized and uncomfortable for a female secretary, and vice versa. A manager may have difficulties in understanding problems related to physical accommodation, simply because they do not apply to him.

Anthropometric measures are usually expressed as percentiles. The most common are the 5th, 50th and 95th percentile measures (Table 3.1). Anthropometric data are usually normally distributed (Figure 3.2) (Roebuck *et al.*, 1975). A normal distribution is characterized by its mean value and its standard deviation (SD). As long as we know these two values of distribution, it is possible to calculate any percentile value. For example, the 95th percentile equals the mean value plus

Table 3.1 Explanation of percentile measures

Percentile	Description
5th	5% of the population is smaller
50th	Average value
95th	95% of the population is smaller

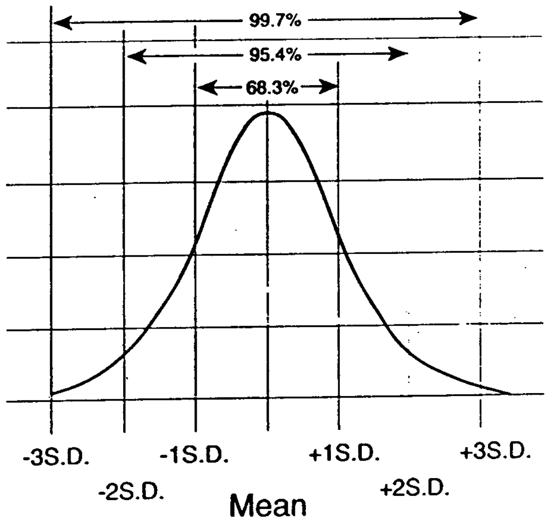


Figure 3.2 Anthropometric data are usually normally distributed

1.65 SD and the 5th percentile equals the mean minus 1.65 SD (Figure 3.2).

The common procedure is to design for a range of population from the 5th percentile (small operator) to the 95th percentile (large operator). The choice of 5th and 95th percentiles is traditional, although one can argue that a greater percentile range should be used. But many ergonomists consider that it is impossible to include extremes of the population, such as dwarfs and giants, in the common design range. For example, the seat of a height-adjustable chair in the USA must adjust between 16 and 20.5 in., which roughly corresponds to the range established by 5th percentile females and 95th percentile males, although some users may be smaller or larger (see Human Factors Society, 1988). Similarly, it would not be practical to make door openings 8 feet tall, although this may be required by a giant.

The greater the design range, the greater the cost. It is more expensive to design for the 5th to 95th percentile range than for the 10th to 90th percentile range. The percentile value selected is largely a political decision, and companies may adopt different policies. One potentially controversial question is whether one should design for the worker population at hand, e.g. the 5th to 95th percentile male, or if one should extend the range to 5th percentile female workers in order to provide 'equal physical access' to females.

There may be reasons to think that workers in a specific manufacturing plant have different body size and are not typical of the population at large. These were the concerns in a study we performed for IBM Corporation in San Jose (Helander and Palanivel, 1990) At this location there were about 1000 female microscope

operators, many of whom had recently arrived to the USA from Asia and were shorter than the 5th percentile US female. Many operators had to stretch to be able to get to the eyepiece and they could not put their feet on the floor. We measured 17 different anthropometric measures of 500 operators and calculated the means, standard deviations, and 5th and 95th percentile measures. These measures were used to specify the appropriate measures for the microscope workstation.

We will explain below how anthropometric measures can be translated into workstation design measures by using the 'anthropometrics design motto':

Anthropometrics design motto

- Let the small person reach.
- Let the large person fit.

These principles imply that reach distances should be designed for the small, 5th percentile individual, whereas clearance dimensions should be designed for the large, 95th percentile individual. A simple case of anthropometric design is illustrated in Figure 3.3. The 5th percentile female and 95th percentile male measures are illustrated for a sitting workplace. Note that the popliteal height (from the sole of the foot to the crease under the knee) is 36 cm (14.0 in.) for 5th percentile females and 49 cm (19.2 in.) for 95th percentile males. These values may actually differ slightly in different anthropometric tables. Note also that the popliteal height (and other measures) are taken without shoes, so that for design purposes one must add the height of the heel of the shoe (about 3 cm). The appropriate range of adjustability for a chair-seat height is then 39–52 cm (15–20.2 in.). The distance from the floor to the elbow is obtained by adding the popliteal height, sitting elbow height and shoe height (3 cm). This measure is 57–81 cm (22–32 in.) and it can be used to select appropriate table height.

As illustrated in the right-hand part of Figure 3.3, there are two different ways to compensate for anthropometric differences. One can use either a height-adjustable chair plus a foot rest, or a height-adjustable chair plus a height-adjustable table. Both arrangements will make it possible to support the feet and have the table at elbow height. The height-adjustable table is more expensive than the foot

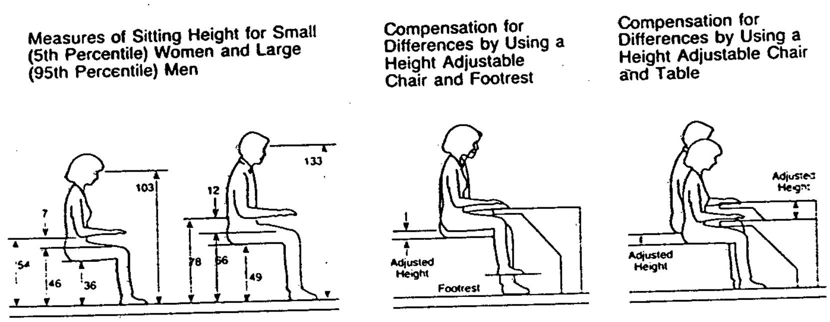


Figure 3.3 Comparison of anthropometric measures (cm) for a sitting 5th percentile female and a sitting 95th percentile male – height-adjustable chairs and tables can be used to compensate for these differences

rest, but it is more comfortable to rest the feet on the floor than to use a foot rest.

In many offices (including the author's) the table height has been set once and for all. The table can indeed be raised and lowered, although not easily. The height-adjustable chair is rarely changed more than once per day. The implications are that for individuals who have their own workstation, ease of adjustability is not crucial. But for people who share a workstation, for example shift workers, adjustability becomes essential (Shute and Starr, 1984). Most of the microscope workers at IBM worked three shifts, so adjustability of the workstation was important. Microscope work is an exacting task. It is necessary to adjust the eye pieces to the exact level of the eyes, the table so that it is convenient to reach microscope controls, and the chair to be able to put the feet on the floor. This is a complex case of adjustability, since there are three interacting elements of adjustability.

3.2 Definition of Anthropometric Measures

The most complete source of anthropometric measures has been published by the US National Aeronautics and Space Administration (NASA, 1978). This reference publication contains measures of 306 different body dimensions, from 91 different populations around the world. About half of the populations are aeroplane pilots, which illustrates the great importance attributed to the anthropometric design of cockpits. Anthropometric investigations have been supported by the Air Force in the USA and many other countries, but surprisingly there is a lack of civilian anthropometric measures. In the USA there has actually never been a comprehensive civilian anthropometric investigation. The measures listed in Table 3.2 are adapted from the data reported by McConville *et al.* (1981), who extrapolated civilian body measures by using data from the military. The measures are also illustrated in Figure 3.4.

Some of the anthropometric measures have Latin names. This is practical, since they refer to bone protrusions on the human body. For example, the tibial height is the height of the proximal medial margin of the tibia, a bone protrusion on the tibia under the knee cap. The acromion height refers to the highest point of the shoulder blade, and the popliteal height is the height from the sole of the foot to the crease under the knee between the upper and the lower leg.

The anthropometric measures illustrate that there are large differences between the sexes. For many measures, the 5th percentile (small male) is about the same size as the 50th percentile (average) female. For example, the inside diameter of the hand grip (measure 17) is 4.3 cm for a 50th percentile female and 4.2 cm for a 5th percentile male. This measure is important for design of handtools to fit the size of the tool to the size of the hand. Women often complain that they have to use handtools designed for men, resulting in muscle fatigue of the hand and the arm, lower productivity, and possibly also injuries (Greenburg and Chaffin, 1977). Both the US Department of Defense as well as industry (e.g. General Motors) have taken note and now supply handtools of different sizes for males and females.

All the measures listed in Table 3.2 have implications for manufacturing. The measurements and their implications are explained below.

1. *Tibial height*. This measure is important for manual materials handling. Items located between the tibial height and the

Table 3.2 US civilian body dimensions (in cm with bare feet; add 3 cm to correct for shoes) of industrial relevance. Adapted from McConville et al. *(1981)*

	Female			Male		
	5th	50th	95th	5th	50th	95th
Standing						
1. Tibial height	38.1	42.0	46.0	41.0	45.6	50.2
2. Knuckle height	64.3	70.2	75.9	69.8	75.4	80.4
3. Elbow height	93.6	101.9	108.8	100.0	109.9	119.0
4. Shoulder (acromion) height	121.1	131.1	141.9	132.3	142.8	152.4
5. Stature	149.5	160.5	171.3	161.8	173.6	184.4
6. Functional overhead reach	185.0	199.2	213.4	195.6	209.6	223.6
Sitting						
7. Functional forward reach	64.0	71.0	79.0	76.3	82.5	88.3
8. Buttock-knee depth	51.8	56.9	62.5	54.0	59.4	64.2
9. Buttock-popliteal depth	43.0	48.1	53.5	44.2	49.5	54.8
10. Popliteal height	35.5	39.8	44.3	39.2	44.2	48.8
11. Thigh clearance	10.6	13.7	17.5	11.4	14.4	17.7
12. Sitting elbow height	18.1	23.3	28.1	19.0	24.3	29.4
13. Sitting eye height	67.5	73.7	78.5	72.6	78.6	84.4
14. Sitting height	78.2	85.0	90.7	84.2	90.6	96.7
15. Hip breadth	31.2	36.4	43.7	30.8	35.4	40.6
16. Elbow-to-elbow breadth	31.5	38.4	49.1	35.0	41.7	50.6
Other dimensions						
17. Grip breadth, inside diameter	4.0	4.3	4.6	4.2	4.8	5.2
18. Interpupillary distance	5.1	5.8	6.5	5.5	6.2	6.8

1 in. = 2.54 cm.

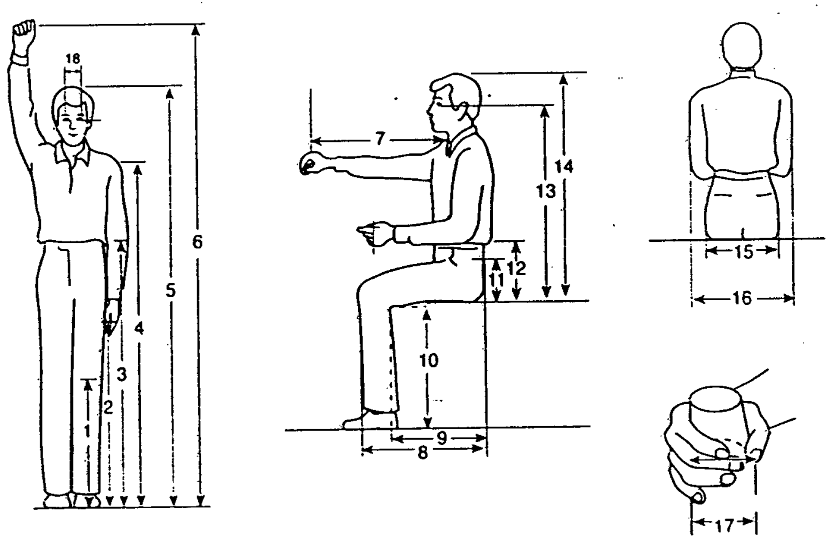


Figure 3.4 Illustration of the anthropometric measures given in Table 3.2

knuckle height must usually be picked up from a stooped position.

2. *Knuckle height*. This height represents the lowest level at which an operator can handle an object without having to bend the knees or the back. The range between the knuckle height and

the shoulder height is ideal for manual materials handling and should be used in industry.

3. *Elbow height.* This is an important marker for determining work height and table height.
4. *Shoulder (acromion) height.* Objects located above shoulder height are difficult to lift, since relatively weaker muscles are employed. There is also an increased risk of dropping items.
5. *Stature.* This is used to determine the minimum overhead clearance required to avoid head collision.
6. *Functional overhead reach.* This is used to determine the maximum height of overhead controls.
7. *Functional forward reach.* Items that are often used within the workstation should be located within the functional reach.
8. *Buttock-knee depth.* This defines the seat depth for chairs and clearance under the work table.
9. *Buttock–popliteal depth.* This is used to determine the length of the seat pad.
10. *Popliteal height.* This is used to determine the range of adjustability for adjustable chairs.
11. *Thigh clearance.* Sitting elbow height and thigh clearance help to define how thick the table top and the top drawer can be.
12. *Sitting elbow height.* Sitting elbow height and popliteal height help to define table height.
13. *Sitting eye height.* Visual displays should be located below the horizontal plane defined by the eye height.
14. *Sitting height.* This is used to determine the vertical clearance required for a seated work posture.
15. *Hip breadth.* This is used to determine the breadth of chairs and whole body access for clearance.
16. *Elbow-to-elbow breadth.* This is used to determine the width of seat backs and the distance between arm rests.
17. *Grip breadth, inside diameter.* This is used to determine the circumference of handtools and the separation of handles.
18. *Interpupillary distance.* This is an important measure in determining the adjustability of eyepieces on microscopes.

To reduce measurement error, anthropometric measures are gathered for minimally clothed men and women who are standing or sitting erect. People in industry are, however, usually fully clothed and stand or sit with a more relaxed posture. With shoes on, the height measures in Table 3.2 should be increased by approximately 3.0 cm. To compensate for postural slump, 2.0 cm is subtracted from standing height and 4.5 cm for sitting height (Brown and Schaum, 1980).

The measure of functional forward reach assumes that there is no bending from the waist or the hips. By bending from the waist, the forward function reach can be increased by about 20 cm and bending from the hips increases reach by about 36 cm (Eastman Kodak, 1983). Since a person cannot bend at the waist or hips for an extended time, these extra allowances should be used only for occasional, short-duration tasks.

There are many different anthropometric databases in use, some of which are fairly dated and may not reflect the fact that the population keeps getting taller. But it may also be the case that some anthropometric data are inaccurate and researchers have not used

enough precautions in obtaining accurate measurements. Anthropometric measures are well defined, and there are standard procedures for taking them. There are also special tools and equipment available for taking the measures (see Roebuck *et al.*, 1975).

3.3 Using Anthropometric Measures for Industrial Design

In the past, most research and anthropometric surveys have been initiated by the US Air Force, which presently is developing tools for three-dimensional modelling using computer-aided design. There are already several programs available for computer-aided design including CAR (Crew station Assessment of Reach), SAMMIE (System for Aiding Man–Machine Interaction Evaluation), COMBIMAN (Computerized Biomechanical Man-Model), CREWCHIEF, and ADAM and EVE. A review of these models can be found in Kroemer *et al.*, (1988).

Most anthropometric models have been used to model workstations which involve very tight constraints, such as cockpits. In the industrial environment, there are fewer constraints. People can usually move around freely, and there is not a great need for very sophisticated modelling. Anthropometric design of a workstation can be accomplished in a couple of hours with paper and a pen.

Depending upon the application, anthropometry is used differently (Figure 3.5). In designing cars, it has been common to start with the hip joint or hip reference point (HRP) and then 'laying out' the rest

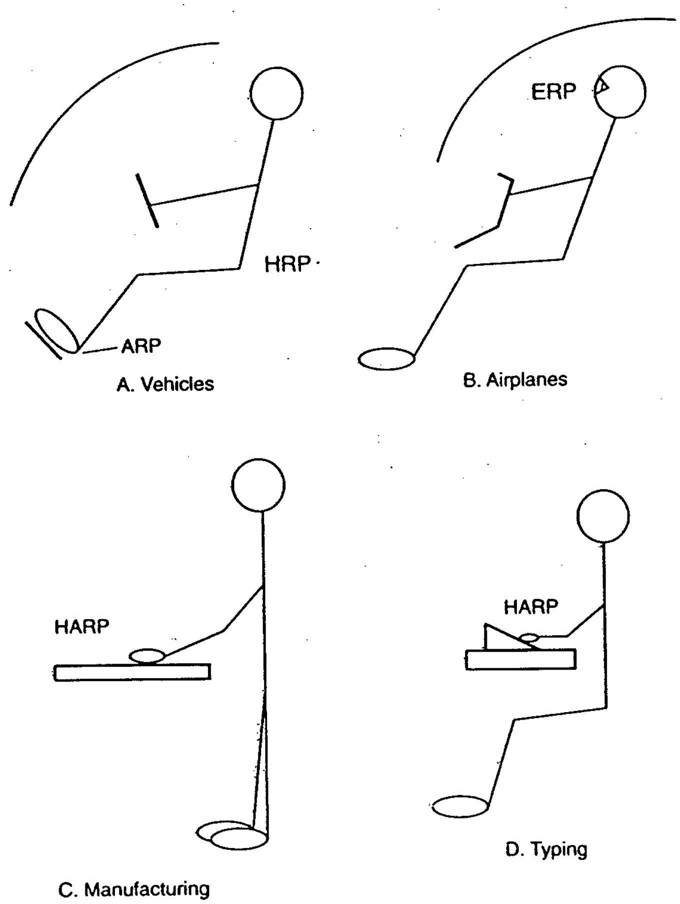


Figure 3.5 Anthropometric design can use different reference points

of the body going up to the head and hands and down to the feet. Some automobile manufacturers (of racing cars) start off with the accelerator reference point (ARP) and then lay out the rest of the body going upwards. In the design of fighter planes, it is important to put the eye at the right height, since there are many displays which must be visible including head-up displays (HUD) which are projected in the windshield. Since the pilot is tied back to the seat, one can make a very accurate estimation of where his or her eye will be. In this case the design will start with the eye or eye reference point (ERP), and the rest of the body can be modelled going downwards.

In manufacturing, for assembly work we advocate the use of a hand reference point (HARP). The ideal location of the hands depends on the task. For heavy manual jobs, the hands should preferably be about 20 cm below elbow height, but for precision tasks with supported under-arms the hands should be about 5 cm above elbow height. Therefore, to design a workstation one first needs to determine the most convenient hand height for the task in question. The rest of the body can then be laid out by finding measures down to the feet and up to the head. Typists have a similar work situation. It may be preferable to start off with a HARP and then lay out the rest of the body.

It is common to design for the range from the 5th to the 95th percentile. In doing so, one may have to add different anthropometric measures. For example, for a sitting workstation with the table top at the elbow height it is necessary to add two measures: popliteal height and sitting elbow height. The addition of anthropometric measures actually produces an inaccurate estimate, since very few individuals are 5th percentile throughout. Typically, a person with a short back may have long legs, or vice versa. Kroemer (1989) showed that the correlation coefficient between stature and sitting eye height is $r = 0.73$, between stature and popliteal height $r = 0.82$, and between stature and hip breadth is $r = 0.37$ ($r = 1.00$ is a perfect positive correlation between two measures, $r = 0$ implies no relationship between two measures). If two 5th percentile measures are added, the resulting measure could be about the 3rd percentile. And if two 95th percentile measures are added, the resulting measure might be the 97th percentile. This problem (with the table top height) would be solved if there were a single measure for sitting elbow height in the anthropometric tables. However, this measure is not one of the 306 defined in NASA's anthropometric tables (NASA, 1978).

Despite several sources of error in anthropometric data, it is usually possible to estimate anthropometric measures with an accuracy of about 1 cm. This is satisfactory for industry. In fact, individuals sitting at a workstation do not have the sensitivity to judge changes smaller than 1 cm (Helander and Little, 1993). If the chair height is raised or lowered by 1 cm, the chair user will not notice the difference.

3.4 Procedure for Anthropometric Design

A procedure for anthropometric design is presented below.

1. *Characterize the user population.* What anthropometric data are available? Can existing anthropometric data be used with the present population? If there are no valid data, consider creating a database by obtaining measures of the existing workforce.
2. *Determine the percentile range to be accommodated in the workstation design.* If the workforce is dominated by either men

or women it would make sense to design for the predominant sex, for example by using 5th–95th percentile male or 5th–95th percentile female measures. On the other hand, it may be an issue of equality to provide 'accessibility' for the other sex. If so, one would design from the 5th percentile female to the 95th percentile male population.

3. *Let the small person reach and let the large person fit.* Determine reach dimensions (5th percentile) and clearance dimensions (95th percentile) for the work situation that is analysed. An example is given in Figure 3.6. In this manufacturing task, the operator is sitting on a chair with his or her hands at elbow level and manipulating objects 6 cm above the table height. Two important reach measures are the popliteal height from the chair seat to the floor and the buttock–popliteal depth (see Table 3.2). Operators should not sit with dangling feet but should be able to reach the floor. An adjustable chair must therefore adjust to a low level corresponding to the 5th percentile. The buttock–popliteal depth should be the 5th percentile, because if it is longer a small operator will not be able to reach to the back support with his or her buttocks. A clearance dimension (*D*) is created under the table. Assuming the table is height adjustable and can be lowered 10 cm below elbow height, will there then still be enough space for the thighs?
4. *Find the anthropometric measures that correspond to the workstation measures.* The calculations for the 5th percentile female and the 95th percentile male operator are shown in Figure 3.6. The anthropometric measures are added starting from floor level. By using the popliteal height and adding 4 cm for shoes, the required range of seat-height adjustability is calculated to be 39.5–52.5 cm. The sitting elbow height for the 5th percentile

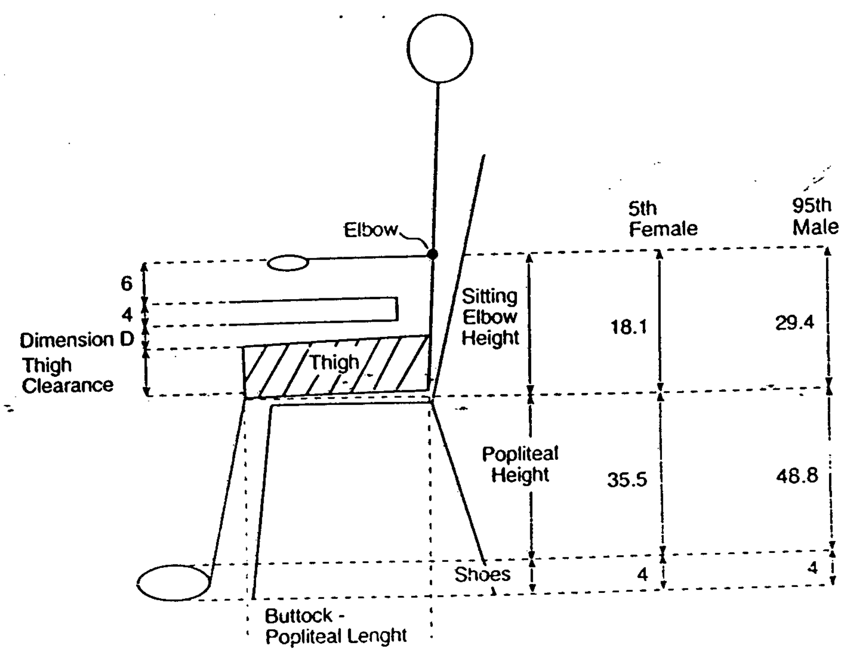


Figure 3.6 *Anthropometric measures used to calculate the adjustability of seat height and table height*

operator is 18.1 cm and for the 95th percentile operator 29.4 cm. From the sitting elbow height, deduct the thickness of the product (6 cm). This means that the distance from the chair seat to the top of the table is 12.1 cm for the 5th percentile and 23.4 cm for the 95th percentile. Adding these measures to the seat-height adjustability gives a required table height adjustability of 51.6–75.9 cm (or 52–76 cm).

Deducting further, bearing in mind the thickness of the table top, we find that for the 5th percentile there is 8.1 cm of clearance between the chair seat and the table and for the 95th percentile there is 19.4 cm of clearance. Since the thigh clearance (see Table 3.2) is 10.6 and 17.7 cm, respectively, a small female operator will not have enough space, but a large male will be able to fit his legs under the table.

5. It is sometimes difficult to illustrate a work situation using an anthropometric model. Anthropometric measures are static, and in the real world there are many dynamic elements. Operators reach for tools and parts and swing around in the chair. To evaluate the dynamic aspects of a workstation appropriately, one may construct a full-scale mock-up out of cardboard or styrofoam. This will not usually take more than a couple of hours. The purpose is then to have people of different sizes testing out the workstation by moving their body and simulating the task. Through the full-scale mock-up it may be possible to identify features of the workstation which need to be redesigned.

3.4.1 Exercise: Designing a Microscope Workstation

Using the set-up of the microscope workstation shown in Figure 3.7, calculate adjustability ranges for seat height, table-top height, and microscope eyepiece eye height (measures *A*, *B* and *C* in Figure 3.7).

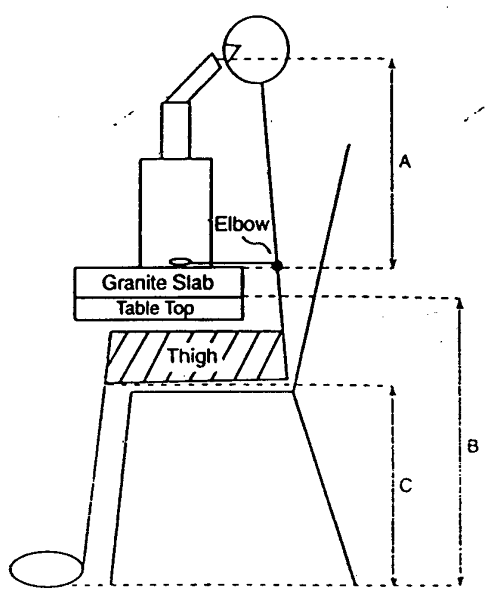


Figure 3.7 Example: designing a microscope workstation

Design for a 5th to 95th percentile female population. There are several assumptions:

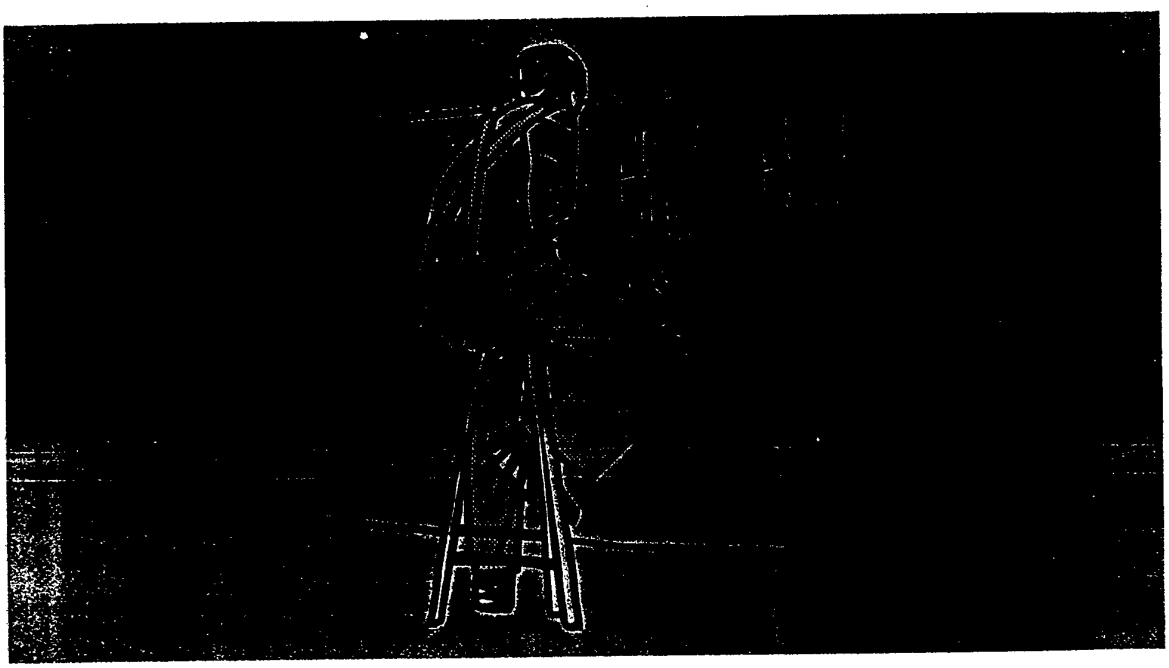
1. There is no footrest.
2. The shoes are 4 cm high.
3. In the upper part of the body from the elbow height to the shoulder height there is a postural slump of 2 cm.
4. When looking into the microscope the operators bend the head forward about 30°, which moves the position of the eye downwards by 1.5 cm.
5. The hands are manipulating focusing controls at elbow height.
6. The arms are horizontal and resting on the granite slab.
7. The table top is 3 in. high. There is also a 4 cm thick granite slab on top of the table to reduce vibration.

Answer

Use dimensions listed in Table 3.2.
Measure *A* : 45.9–46.9 cm
Measure *C* : 39.5–48.3 cm
Measure *B* : 53.6–72.4 cm

A Guide to the Ergonomics of Manufacturing

Martin Helander



Taylor & Francis

effort, where engineers and workers can collaborate in arranging a workstation.

Predetermined time-and-motion studies (PTMS) such as methods time measurement (MTM), MOST, and WORK FACTOR have primarily been used for predicting and quantifying the time it will take to assemble a product (Konz, 1990). PTMS measurements can then be used to divide a large task into several parts, thus balancing the work between different workers. PTMS is also used as a basis for salary negotiations. However, PTMS could have a much wider usage. It could be used to evaluate the design of a product, and alternatives for organizing a workstation. But this is rarely done – perhaps because there are so many different options for workstation design, it is difficult to understand where to start. Some guiding principles are clearly needed, such as the principles resting on ergonomics knowledge that are described below.

11.8 Principles for the Design of Workstations

1. *Keep the number of items that are touched by the hand to a minimum.* Minimize the number of hand tools, the number of different parts, and the number of controls. The number of parts and the number of necessary tools depend on the product to be manufactured. It is important for product designers to understand the implications of their design in terms of manual labour. Why use five varieties of screw when two are enough? Why not combine parts such as incorporating washers with the screws?
2. *Arrange the items (controls, hand tools and parts) so that the operator can adjust his/her posture frequently.* Sometimes the location of items tie up workers in impossible work postures. There are many examples of industrial machinery which must be operated using a foot control. For example, in using an industrial punch press the operator must hold the work item with both hands and press the foot control to initiate the pressing action. Using just one foot causes one-sided strain that is likely to lead to back problems. It must be possible to move the foot control so that it can be operated with either foot at the worker's convenience.
3. *Consider preferences in hand movements and handedness.* People can move their hands both faster and with much better precision through an arc than they can horizontally or vertically. Imagine that you are drawing a straight line on a piece of paper. It is difficult to get the line straight if it is drawn horizontally or vertically. It is easier to draw if the paper is turned at an angle so that the hand can move outwards from the body, such as in the movement envelopes shown in Figure 11.6. This is because there are only a few active joints in the arm, typically only the elbow joint moves. But for drawing a horizontal or a vertical line there are many more active joints and many muscles that have to interact, which makes the movement more complex.
   Handedness is important in the design of hand tools, particularly those intended for tasks which require skill and dexterity. Assembly tasks do require skill and dexterity, and thus hand tools for left-handed individuals.
4. *Organize items in the workplace.*
   (a) Distinguish between primary and secondary items. Primary items are those that are used most frequently and secondary

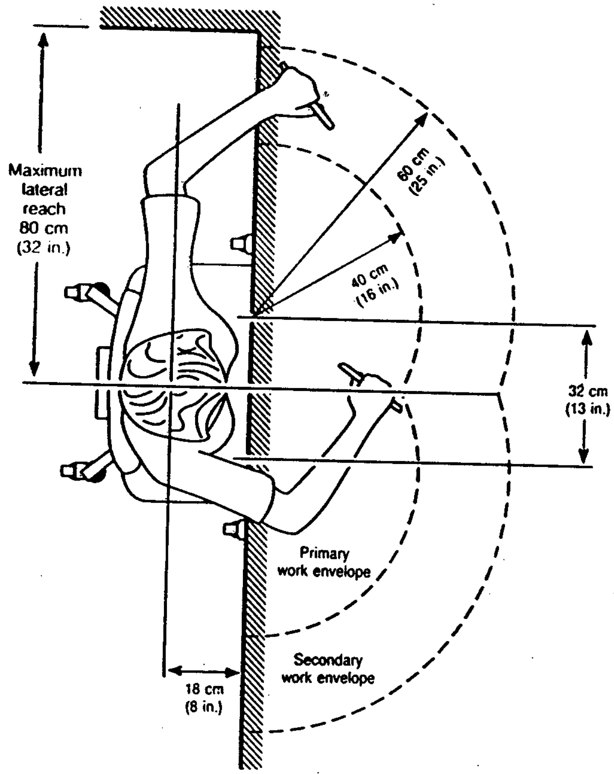


Figure 11.6 Arrangement of a workstation, showing primary and secondary movement envelopes

items are those that are not used as frequently. List all the parts and classify them as primary or secondary items.

(b) Divide the tasks into subtasks, each forming a logical unit. For very short tasks this may not be important, but for more comprehensive tasks it is desirable.

(c) Divide the worktable into several areas, one for each subtask. This may be practical only for comprehensive tasks where there are many items to keep track of. Organizing the items for each subtask is practical and makes it easier for the operator to think of the task.

(d) Identify primary and secondary movement envelopes on the worktable. The functional reach for a 5th percentile female worker is about 40 cm (16 in.) and determines the limit of the primary work envelope (Figure 11.6). Put a primary item in the primary envelope. Secondary items should be put in the secondary envelope, but within a reaching distance of about 60 cm (24 in.).

(e) Locate items such as bins and tools so they can be used sequentially for each subtask. A procedural order helps in organizing the task and facilitates task learning and productivity. A well-organized workstation will save time and is productive. The location of parts, hand tools and controls according to the primary and secondary importance helps in organizing the workstations.

11.9 Recommended Reading

Much information relevant to the design of industrial workstations is available in military design guidelines. Although military tasks are different from industrial tasks, the designer of industrial workstations may consult such resources for ideas. The *Human Factors Design Handbook* (Woodson, 1981) is a comprehensive collection of design guidelines with many illustrations. *Human Engineering Guide to Equipment Design* (Van Cott and Kinkade, 1972) is an inexpensive and useful reference book. An example of the type of information available is given in Figure 11.7.

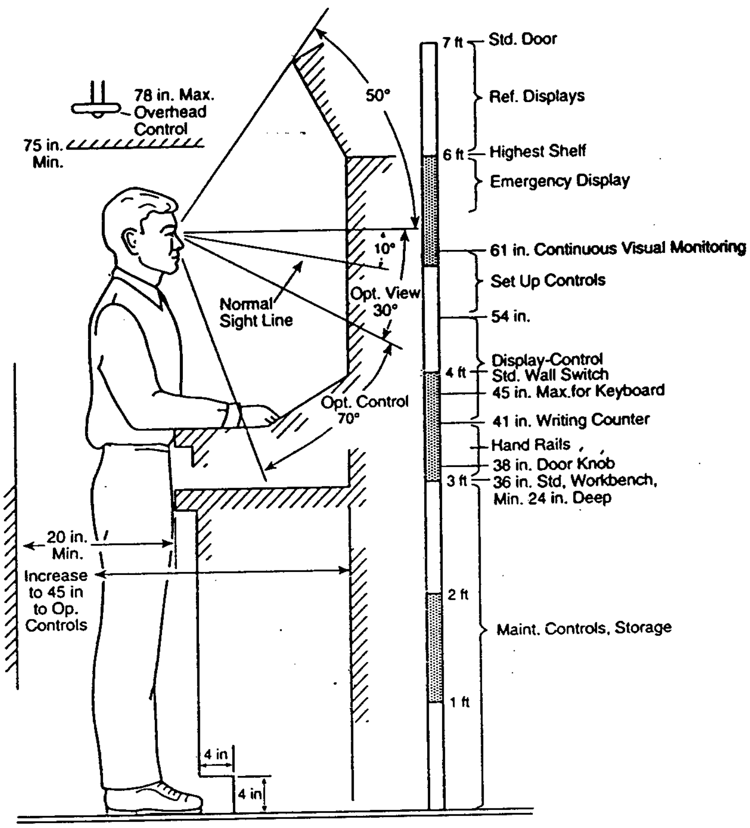


Figure 11.7 Design of a console workstation for a standing operator. Although this workstation was conceived for military applications, it is equally relevant for process control

11.9 Recommended Reading

Much information relevant to the design of industrial workstations is available in military design guidelines. Although military tasks are different from industrial tasks, the designer of industrial workstations may consult such resources for ideas. The *Human Factors Design Handbook* (Woodson, 1981) is a comprehensive collection of design guidelines with many illustrations. *Human Engineering Guide to Equipment Design* (Van Cott and Kinkade, 1972) is an inexpensive and useful reference book. An example of the type of information available is given in Figure 11.7.

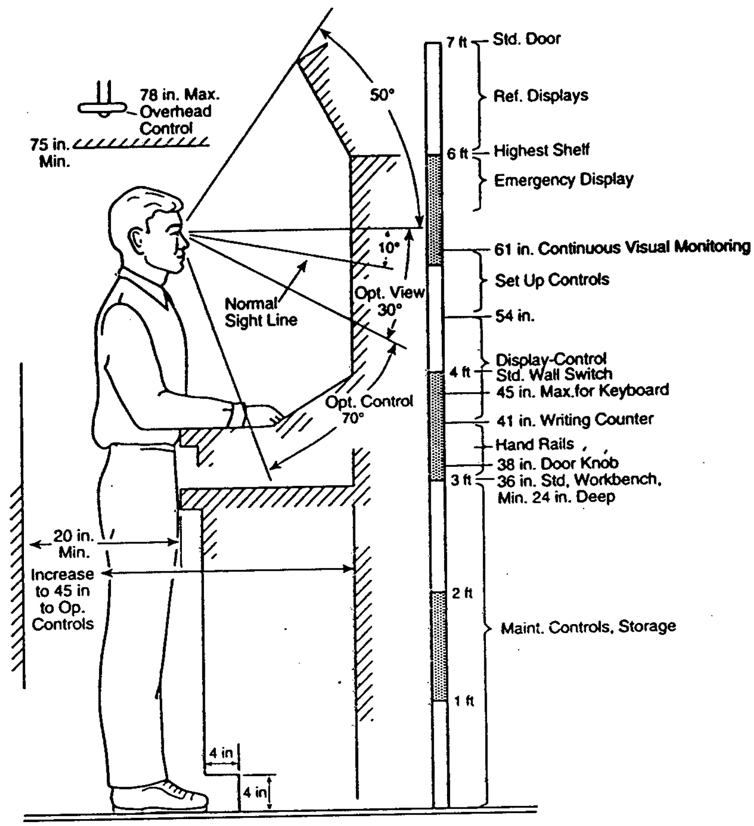


Figure 11.7 Design of a console workstation for a standing operator. Although this workstation was conceived for military applications, it is equally relevant for process control

PART ONE THE ERGONOMIC KNOWLEDGE BASE

1

The Anatomical and Mechanical Structure of the Human Body

OVERVIEW

Body dimensions of many people on earth are only estimated. For Europeans and North Americans, the measurements of adult civilians must be derived from data taken on soldiers. Correlations among measurements allow us to establish design rules for things that must "fit" the body.

Biomechanically, one can describe the human body as a basic skeleton whose parts are linked in joints; the members have volumes and mass properties and are moved by muscles. Understanding the properties, capabilities, and limitations allows us to design equipment and tools that use and enhance human strengths.

DEVELOPMENT

Human species development may be compared to the growth of a bush and its branches. Some branches develop and die while others grow more and more twigs, some of which vanish while others flourish. In the process, variations occur in body dimensions of different groups of people. Ergonomics must take these variations into account.

The development of the human race can be traced by fossils and by reconstruction of mitochondrial DNA over several million years in Africa, and for hundreds of thousands of years in Europe and Asia (Diamond, 1988; Gould, 1988; Asimov, 1989).

Current theory holds that the Austrolopithecine was a predecessor of the genus homo about 3 million years ago in Africa, where *homo erectus* then developed. One humanoid branch started about 250 thousand years ago and remained in Africa. Another branch developed 60 or 70 thousand years later. Some of its members stayed in Africa and others spread all over the earth.

Remains of anatomically modern humans who lived about 130 to 180 thousand years ago have been found in South Africa and in the Levant. There and in central Europe, about 150 thousand years ago, the *Neanderthal* emerged. Neanderthals apparently were stocky, heavy-set, and cold-adapted with a brain as big as ours. They lived tens of thousands of years side-by-side with *Cro-Magnons*, but vanished about 30 thousand years B.C. Cro-Magnons lived in the area of what is today Israel around 90 thousand years ago; their stock probably grew into *homo sapiens*.

Popular notions about the different appearances of Cro-Magnons and Neanderthals are mostly based on conjecture, often Hollywood movie style. For example, there is no indication that the Cro-Magnons were dark skinned, or the Neanderthals light. Furthermore, there is no evidence of violent struggles for superiority between the two races.

Bushmen and Pygmies probably occupied most of subequatorial Africa until about two thousand years ago. Bantu-speaking people living in the area of Cameroon and Congo learned to use iron, developed agriculture, and domesticated animals. The flourishing Bantu then drove Bushmen and Pygmies into areas unsuitable for agriculture. Subsequently, 60 million Bantu occupied half the African continent.

From Africa, homo spread over the earth. About 50 thousand years ago, Australia was settled by early humans who arrived from eastern Indonesia. Their descendants became the Aboriginal population. Most of the current inhabitants of Indonesia, the Philippines, and parts of Southeast Asia are descendants of a population that emigrated from Taiwan about six thousand years ago.

The Americas were settled by emigrants from Asia who crossed what was then the Bering land bridge to Alaska, probably about 15 thousand years ago. It is believed that bands of hunters passed through today's Canada into the area of the present United States. Their descendants populated the entire hemisphere, becoming the ancestors of North and South American Indians.

Europe, after its long history of pre-Neanderthals, Neanderthals, and Cro-Magnons, has been reconstituted twice fairly recently: about eight thousand years ago by farmers from the Near East, and about two thousand years later by Indo-Europeans from southern Russia.

In 1776, the German anthropologist Johann Friedrich Blumenbach (1753–1840) divided groups of humans into "races": Caucasians, Mongolians, Malayans, Ethiopians, and (native) Americans (Asimov, 1989).

Thus, the human stock with its many current branches appears African in origin, and about a quarter-million years old. Today, the number of people is growing fast: "population explosions" are occurring in some parts of the earth. The total number of humans was about 10^9 (one thousand million, i.e., one billion) around 1800. The second billion was reached by 1930. The third billion was present in 1960, the fifth in 1987. Just before the year 2000, the earth's population is likely to reach six billion. If current birth and death rates continue, 80 billion people will live on earth in 2100, and 150 billion crowd it in 2125.

In the late 1980s, about 90 million people were added each year to the earth's population. The current projection is an increase of approximately one billion people every ten years. Most will be born in third-world countries where food supplies are insufficient even now; of the five billion people on earth in 1987 about 1.2 billion lived in industrialized countries.

Emigration from certain areas and immigration to others are on a much smaller scale than population growth but can be locally of great importance. In North America, for example, during the last few centuries, waves of immigrants from certain geographical areas have been changing the composition of the inhabitant population, replacing most native Indians by Europeans. In today's United States, the influx of Cubans and Haitians is strongly felt in Florida, the arrival of South Americans affects southwestern states, and Asians are very evident along the Pacific coast.

Marco Polo (1254–1324) traveled to the Far East and stayed in China for 20 years. There he found a nation far in advance of Europe in population, wealth, technology, and the civilized amenities. He returned in 1292 to Italy, where he was taken prisoner in the war between Venice and Genoa. While detained, he began to dictate his reminiscences of China, published in 1298. Although largely disbelieved, his book was immensely popular, and stimulated much interest in the study of other countries (Asimov, 1989).

ANTHROPOLOGY AND ANTHROPOMETRY

Anthropology, the study of mankind, was primarily philosophical and esthetical in nature until about the middle of the nineteenth century. Yet, the size and proportions of the human body have always been of interest to artists, warriors, and physicians. Physical anthropology is that scientific subgroup in which the body, particularly bones, is measured and compared. In the middle of the nineteenth century, the Belgian statistician Adolphe Quételet first applied statistics to anthropological data. This was the beginning of modern *anthropometry*, the measurement of the human body. By the end of the ninteeenth century, anthropometry was a widely applied scientific discipline, used both in measuring the bones of early people and in assessing the body sizes and proportions of contemporaries. A new offspring, *biomechanics*, had already developed. Engineers have become highly interested in the application of anthropometric and biomechanical information.

In 1316, Mondino D. Luzzi, professor at the medical school of Bologna, Italy, published the first book devoted entirely to anatomy. The Flemish anatomist Andreas Vesalius, in the early sixteenth century, upset many traditional but false Greek and Egyptian notions about anatomy of the human body in his book De Corporis Humani Fabrica, *concerning the structure of the human body. His book contained careful illustrations of anatomical facts, drawn by a student of Titian (Asimov, 1989).*

Standardization of measuring methods became necessary, achieved primarily by conventions of anthropologists in Monaco, 1906, and in Geneva, 1912. Bony landmarks were established on the body, to and from which measurements were taken. In 1914 an authoritative textbook was published, Martin's *Lehrbuch der Anthropologie*, editions of which shaped the discipline for several decades. Beginning in the 1960s, new engineering needs for anthropometric information, newly developing measuring techniques, and advanced statistical considerations stimulated the need for updated standardization. In the 1980s, the International Standardization Organization (ISO) began efforts to normalize anthropometric measures and measuring techniques worldwide.

Measurement Techniques

Body measurements are usually defined by the two endpoints of the distance measured. For example, forearm length is often measured as elbow-to-fingertip distance; stature (height) starts at the floor on which the subject stands, and extends to the highest point on the skull.

EXAMPLE

There are four customary positions of the subject for measurement of stature: (1) standing naturally upright; (2) standing stretched to maximum height; (3) leaning against a wall with the back flattened and buttocks, shoulders, and back of the head touching the wall; or (4) lying on one's back. The difference between measures when the standing subject either stretches or just stands upright can easily be 2 cm or more. Lying supine results in the tallest measure. This example shows that standardization is needed to assure uniform postures and comparable results.

Specific terminology and measuring conventions have been described by Garrett and Kennedy (1971); Gordon, Churchill, Clauser, Bradtmiller, McConville, Tebbetts, and Walker, (1989); Hertzberg (1968); Kroemer, Kroemer, and Kroemer-Elbert (1990); Lohman, Roche, and Martorel (1988); NASA/Webb (1978); Pheasant (1986); Roebuck (1993); and Roebuck, Kroemer, and Thomson (1975). These publications provide exhaustive information about traditional measurement procedure and techniques.

APPLICATION

The following terms are used in classical anthropometry:

Height—is a straight-line, point-to-point vertical measurement.

Breadth—is a straight-line, point-to-point horizontal measurement running across the body or a segment.

Depth—is a straight-line, point-to-point horizontal measurement running fore-aft the body.

Distance—is a straight-line, point-to-point measurement between landmarks on the body.

Curvature—is a point-to-point measurement following a contour; this measurement is usually neither closed nor circular.

Circumference—is a closed measurement that follows a body contour; hence this measurement is not circular.

Reach—is a point-to-point measurement following the long axis of the arm or leg.

For most measurements, the subject's body is placed in a defined upright straight posture, with body segments either in line with each other or at 90 degrees. For example, the subject may be required to "stand erect; heels together; buttocks, shoulder blades and back of head touching a wall; arms and fingers straight and vertical." This is similar to the so-called "anatomical position." The head is often positioned in the Frankfurt Plane: the pupils are on the same horizontal level; the right ear hole (tragus) and the lowest point of the socket (orbit) of the right eye are also on a horizontal plane. When measurements are taken on a seated subject, the flat and horizontal surfaces of feet and foot support are so arranged that the thighs are horizontal, the lower legs vertical, and the feet flat on their horizontal support. The subject is nude, or nearly so, and does not wear shoes. The standard reference planes are the medial (midsagittal), the frontal (or coronal), and the transverse planes, usually thought to meet in the center of mass of the whole body.

Figure 1-1 shows reference planes and descriptive terms. Figures 1-2 and 1-3 illustrate anatomical landmarks on the human body.

Classical measuring techniques. The conventional measurement devices are quite simple. In the Morant technique, one uses a set of *grids*, best attached to the inside corner of two vertical walls meeting at right angles. The subject is placed in front of the grids, and projections of bony landmarks onto the grids are used to determine anthropometric values. Other boxlike jigs with grids are used to provide references for the measurement of head and foot dimensions.

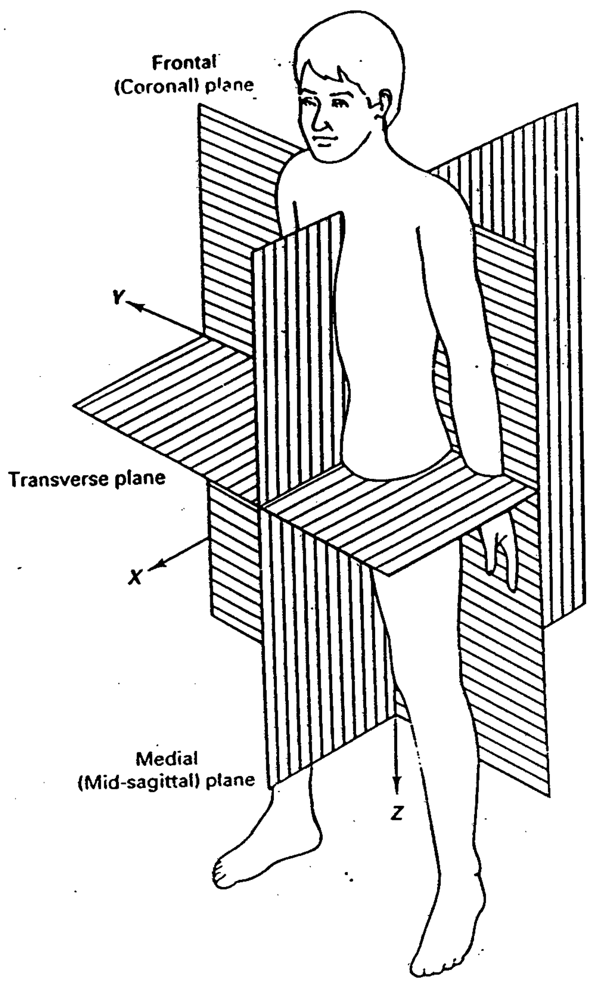


Figure 1-1. Terms and measuring planes used in anthropometry.

Many bony landmarks, however, cannot be projected easily onto grids. In this case, special instruments are used. The most important is the *anthropometer*, a graduated rod with a sliding edge at right angle. The rod can be disassembled for transport and storage, but put together is 2 meters long. (Anthropometric data are traditionally recorded in metric units.) The *spreading caliper* consists of two curved branches joined in a hinge. The distance between the tips of the branches is read from a scale. A small *sliding caliper* can be used for short measurements, such as finger thickness or finger length. A special caliper is used to measure the thickness of skinfolds. A cone is em-

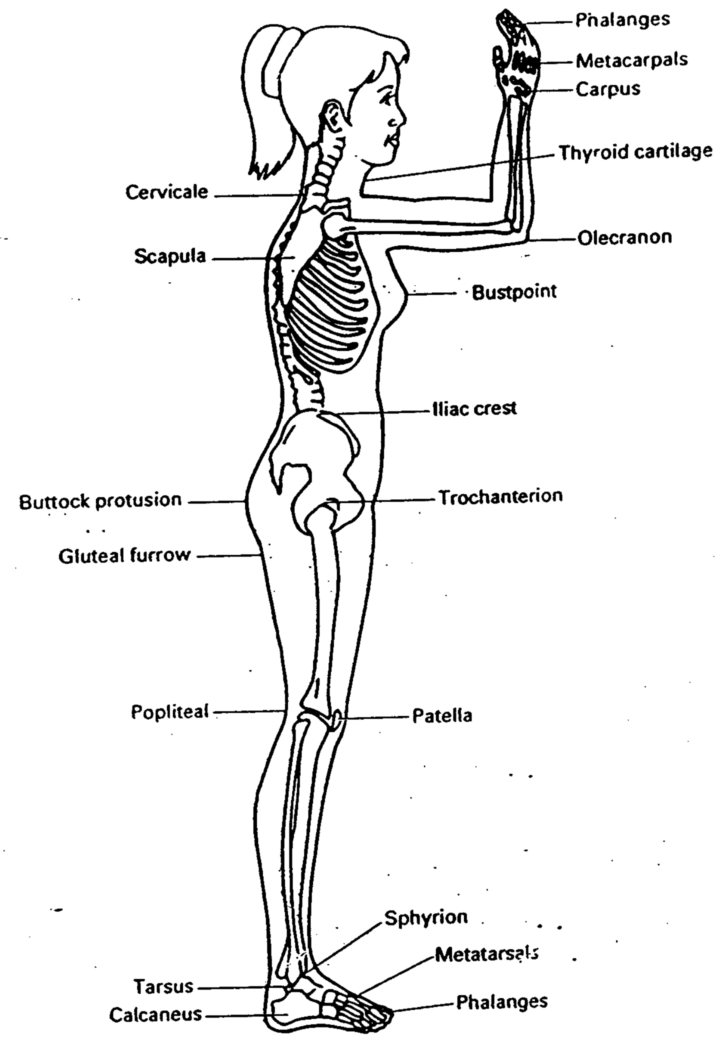


Figure 1-2. Anatomical landmarks in the sagittal view. (From Kroemer, Kroemer, and Kroemer-Elbert, 1990, *Engineering Physiology: Bases of Human Factors/Ergonomics*, 2d ed. With permission by the publisher, Van Nostrand Reinhold. All rights reserved.)

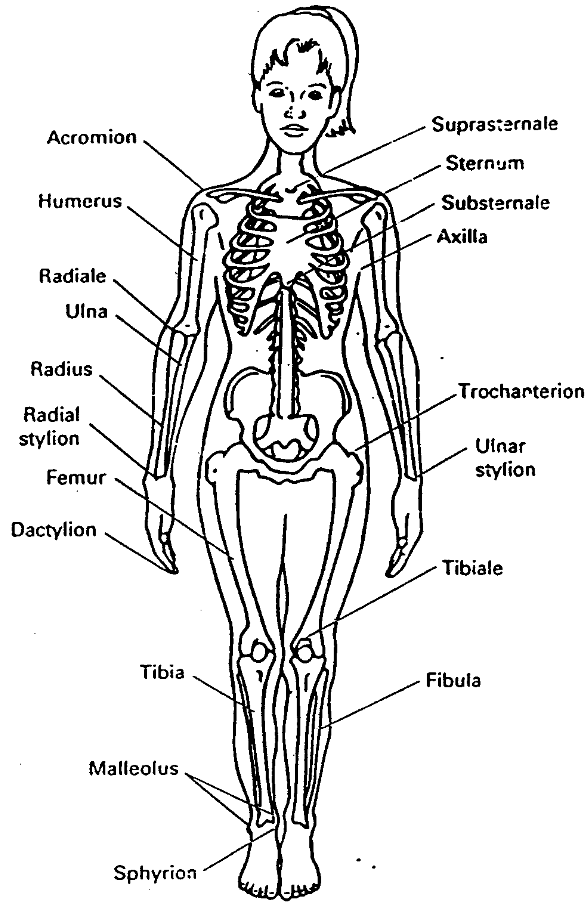


Figure 1-3. Anatomical landmarks in the frontal view. (From Kroemer, Kroemer, and Kroemer-Elbert, 1990. *Engineering Physiology: Bases of Human Factors/Ergonomics*, 2d ed. With permission by the publisher, Van Nostrand Reinhold. All rights reserved.)

ployed to measure the diameter around which fingers can close. Circular holes of increasing sizes drilled in a thin plate serve to measure external finger diameter. Circumferences and curvatures are measured with tapes. A scale is used to measure the weight of the body (Kroemer, Kroemer, and Kroemer-Elbert, 1990). Many other measuring methods can be applied in special cases, such as the shadow technique, use of templates, or casting; they are explained by Gordon, Churchill, Clauser et al. (1989) and by Roebuck, Kroemer, and Thomson (1975).

Most traditional measurement instruments are applied by the hand of the measurer to the body of the subject. This is simple but time consuming. Also, it requires that each measurement and tool be selected in advance, and what was not measured in the test session remains unknown.

A major shortcoming of the classical techniques is that they leave many of the body dimensions unrelated to each other in space. For example, as one looks at a subject from the side, stature, eye height, and shoulder height are located in different undefined frontal planes. Another shortcoming is that contact measurements cannot be made on certain parts of the body, such as the eyes, that are very sensitive.

New measurement techniques. Photographs can record all three-dimensional aspects of the human body. They allow the recording of practically infinite numbers of measurements, which can be taken from the record at one's convenience. Photographs also have drawbacks, however: the equipment (particularly for data analyses) is expensive; the body is depicted in two dimensions: a scale may be difficult to establish; parallax distortions occur; and bony landmarks under the skin cannot be palpated on the photograph.

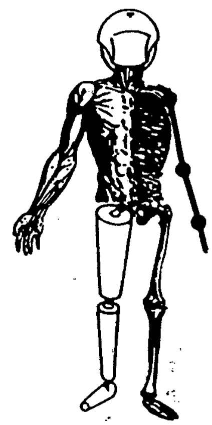
For these and other reasons photographic anthropometry has not been widely used; in spite of many recent technical improvements, such as stereophotometry with several cameras or mirrors, holography, and the use of film and videotape instead of still photography. These methods can extract a large number of datum points from the recorded picture of the body (Coblentz, Mollard, and Ignazi, 1991).

Many techniques for acquiring three-dimensional anthropometric data have been proposed in the past, as described in some detail by Roebuck, Kroemer, and Thomson (1975) and NASA/Webb (1978). Some techniques rely on projecting a regular geometric grid onto the irregularly shaped human body. The projected grid remains regular when viewed along its axis of projection, but appears distorted if viewed at an angle. The displacements of projected grid points from their regular positions can be used to determine the shape of the surface.

The laser can be used as a distance measuring device to determine the shape of irregular bodies (Coblentz, Mollard, and Ignazi, 1991; Zehner, 1986). The body to be measured is rotated, or the sending and receiving units of the laser device rotate around the body.

With the increased use of computer models of the human body, requirements for anthropometric data have become much more complex now than they were just a few decades ago. Most such models represent the long bones of the human body as links, connected in simplified joints, and powered by muscles spanning one or two joints. Computer programs can integrate the recorded data to generate models of the human body, from which desired dimensions and contour identifiers can be extracted (see, e.g., Baughman, 1982; Drerup and Hierholzer, 1985; and Herron, 1973).

The "stick-person" is the seventeenth-century concept of Giovanni Alfonso Borelli, taken up two centuries later by Weber and Weber in their discussion of the mechanics of the legs, by Harless (1860) and von Meyor (1863) in their considerations of body mass properties, and by Braune and Fischer (1889) in their analysis of the biomechanics of a gun-firing infantryman. In 1873 von Meyer modeled body segments as ellipsoids and spheres. This biomechanical model was refined and expanded by Dempster in the 1950s. The Simons and Gardner model of 1960 still depicted body segments as uniform geometric shapes: cylinders for the appendages, neck, and torso, and a sphere for the head. Using equations developed by Barter in 1957, inertial parameters were computed for the geometric forms and the moment for the total body of inertia. This elementary work still is the basis for much of the present biodynamic modeling.



Mathematical-statistical techniques are available to locate specific landmarks and describe three-dimensional surfaces in terms of "facet algorithms," which provide a complete topographic description. The facet approach defines flats, peaks, pits, ridges, ravines, saddles, and hillsides on the human body in ways similar to those used in describing earth contours (Watson, Laffey, and Haralick, 1985).

NEED

It is desirable to replace the traditional heights, lengths, breadths, etc. by three-dimensional coordinates that provide exact point locations from a common origin. This approach should describe static body as well as a moving one. Before such a "system anthropometry" (a term coined by Reynolds — see Kroemer, Snook, Meadows and Deutsch, 1988) can be developed and an effective anthropometric database created, fundamental interrelated problems need solutions. We need an effective data-collection system which supplies accurate and reproducible results, allows immediate digital outputs as well as rapid data transfer to storage, and is fairly inexpensive and easy to use.

Available Anthropometric Information

In the past, interest in the body build of populations other than one's own group was based mostly on curiosity and general "wish to know." More recently, as industry and marketing reach around the globe, body size has become a matter of practical interest to designers and engineers. In the early 1970s, a conference on "ethnic variables in human-factors engineering" first at-

tempted a compilation of world-wide ergonomic information (Chapanis, 1975). A thorough collection of data, available in the mid-1970s, was published in the NASA/Webb (1978) anthropometric sourcebook. Since then, an increasing number of publications describing national populations has appeared in the literature. For example, body sizes of southeast Asians are becoming well known, reflecting both scientific interest and economic concern. Wang, Whin, and Shi (1990) and Li, Hwang, and Wang (1990) demonstrated how proper use of modern technology and statistics allows anthropometric surveys (in this case, of Taiwan) to be performed rapidly and exactly.

Juergens, Aune, and Pieper (1990) attempted to classify the total population of the earth into 20 area groups and to estimate 19 of their main anthropometric dimensions. Because of many voids, much of the data had to be "guesstimated" and certain subgroups (e.g., pygmies) are not represented in this global survey. An excerpt from their global estimates is given in Table 1-1.

TABLE 1-1. AVERAGE ANTHROPOMETRIC DATA (IN CM) ESTIMATED FOR 20 REGIONS OF THE EARTH

	Stature		Sitting height		Knee height, sitting	
	Females	Males	Females	Males	Females	Males
NORTH AMERICA	165.0	179.0	88.0	93.0	50.0	55.0
LATIN AMERICA						
Indian population	148.0	162.0	80.0	85.0	44.5	49.5
European and Negroid population	162.0	175.0	86.0	93.0	48.0	54.0
EUROPE						
Northern	169.0	181.0	90.0	95.0	50.0	55.0
Central	166.0	177.0	88.0	94.0	50.0	55.0
Eastern	163.0	175.0	87.0	91.0	51.0	55.0
Southeastern	162.0	173.0	86.0	90.0	46.0	53.5
France	163.0	177.0	86.0	93.0	49.0	54.0
Iberia	160.0	171.0	85.0	89.0	48.0	52.0
AFRICA						
North	161.0	169.0	84.0	87.0	50.5	53.5
West	153.0	167.0	79.0	82.0	48.0	53.0
Southeast	157.0	168.0	82.0	86.0	49.5	54.0
NEAR EAST	161.0	171.0	85.0	89.0	49.0	52.0
INDIA						
North	154.0	167.0	82.0	87.0	49.0	53.0
South	150.0	162.0	80.0	82.0	47.0	51.0
ASIA						
North	159.0	169.0	85.0	90.0	47.5	51.5
Southeast	153.0	163.0	80.0	84.0	46.0	49.5
SOUTH CHINA	152.0	166.0	79.0	84.0	46.0	50.5
JAPAN	159.0	172.0	86.0	92.0	39.5	51.5
AUSTRALIA (European population)	167.0	177.0	88.0	93.0	52.5	57.0

SOURCE: Juergens, Aune, and Pieper, 1990.

TABLE 1-2. RECENT ANTHROPOMETRIC DATA ON INTERNATIONAL POPULATION SAMPLES: AVERAGE AND STANDARD DEVIATION (ALL IN CM BUT WEIGHT IN KG)

	Sample size N	Stature	Sitting height	Knee height, sitting	Weight
Algerian females (Mebarki and Davies, 1990)	666	157.6 (5.56)	79.5 (5.01)	48.7 (3.61)	61.3 (12.9)
Brazilian males (Ferreira, 1988; cited by Al-Haboubi, 1991)	3076	169.9 (6.7)	—	—	—
Chinese females (Singapore) (Ong, Koh, Phoon, and Low, 1988)	46	159.8 (5.8)	85.5 (3.1)	—	—
Cantonese males (Evans, 1990)	41	172.0 (6.3)	—	—	60.0 (6.2)
Egyptian females (Moustafar, Davies, Darwich, and Ibraheem, 1987)	4960	160.6 (7.18)	83.8 (4.30)	49.9 (2.51)	62.6 (4.37)
Indian males (farmers) (Nag, Sebastian, and Mavlankar, 1980)	13	157.6 (1.7)	—	—	44.6 (1.4)
Indonesian females	468	151.6 (5.4)	71.9 (3.4)	—	—
Indonesian males (Sama'mur, 1985; cited by Intaranont, 1991)	949	161.3 (5.6)	87.2 (3.7)	—	—
Irish males (Gallwey and Fitzgibbon, 1991)	164	173.1 (5.83)	91.1 (3.03)	50.8 (2.77)	73.9 (8.66)
Italian females	753	161.0 (6.4)	85.0 (3.4)	49.5 (3.0)	58.0 (8.3)
Italian males (Coniglio, Fubini, Masali, Masiero, Pierlorenzi and Sagone, 1991)	913	173.3 (7.1)	89.6 (3.6)	54.1 (3.0)	75.0 (9.6)
Jamaican females	30	174.9	85.6	—	67.6
Jamaican males (Carney, Aghazadeh, and Nye, 1991)	123	164.8	83.2	—	61.4

Malay females (Ong, Koh, Phoon, and Low, 1988)	32	155.9 (6.6)	83.1 (3.9)	—	—
Saudi-Arabian males (Dairi, 1986; cited by Al-Haboubi, 1991)	1440	167.5 (6.1)	—	—	—
Sri Lankan females	287	152.3 (5.9)	77.4 (2.2)	—	—
Sri Lankan males (Abeysekera, 1985; cited by Intaranont, 1991)	435	163.9 (6.3)	83.3 (2.7)	—	—
Sudanese males					
Villagers	37*	168.7 (6.3)	—	—	57.1 (7.6)
City dwellers	16*	170.4 (7.2)	—	—	62.3 (13.1)
	48**	166.8	—	—	51.3
Soldiers	21*	173.5 (7.1)	—	—	71.1 (8.4)
	104**	172.8	—	—	60.0
*(Elkarim, Sukkar, Collins, and Dore, 1981) **(Ballal et al., 1982; cited by Intaranont, 1991)					
Thai females	250*	151.2 (4.8)	—	—	—
	711**	154.0 (5.0)	81.7 (2.7)	—	—
Thai males*	250*	160.7 (2.0)	—	—	—
	1478**	165.4 (5.9)	87.2 (3.2)	—	—
*(Intaranont, 1991) **(NICE; cited by Intaranont, 1991)					
Turkish females					
Villagers	47	156.6 (5.2)	79.2 (3.8)	48.6 (2.7)	69.1 (13.8)
City dwellers (Goenen, Kalinkara, and Oezgen, 1991)	53	156.3 (5.5)	78.6 (0.5)	47.1 (0.5)	65.9 (13.0)
Turkish males (soldiers) (Kayis and Oezok, 1991)	5108	170.2 (6.0)	88.8 (3.4)	51.3 (2.8)	63.3 (7.3)

More exact data on specific population samples, taken in recent years, are compiled in Table 1-2.

Variability. Anthropometric data show considerable variability stemming from four sources:

Measurement Variability. Differing care is exercised in selecting population samples, using measurement instruments, storing the measured data, and applying statistical treatments which may yield quite variable information.

Intraindividual Variability. The size of the same body segment of a given person changes from youth to age, depending also on nutrition, physical exercise, and health. Such changes become apparent in "longitudinal" studies, in which an individual is observed over years and decades. Most (but not all) such changes with age follow the scheme shown in Figure 1-4. During childhood and adolescence, body dimensions such as stature change rapidly. From the early 20s into the 50s, little change occurs in general, with stature remaining almost steady. From the 60s on, many dimensions decline, while others—for example, weight or bone circumference—often increase.

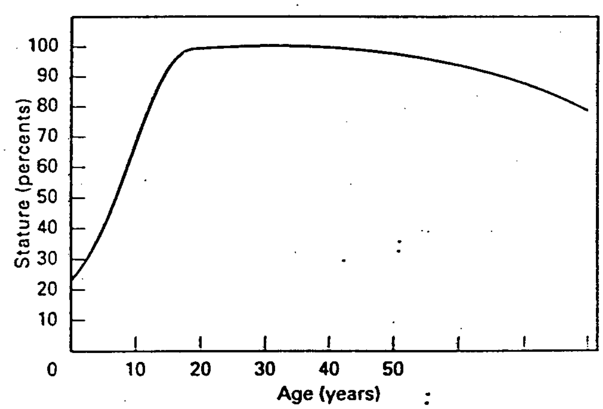


Figure 1-4. Approximate changes in stature with age.

Interindividual Variability. Individuals differ from each other in arm length, weight, height, and other measurements. Data describing a population sample are usually collected in a "cross-sectional" study, in which every subject is measured at the same moment in time. This means that people of different ages, nutrition, fitness, and so on, are included in the sample set. The anthropometric data found in most textbooks, including this one, are gathered in cross-sectional studies.

Secular Variations. There is some factual and much anecdotal evidence that people nowadays are larger, on average, than their ancestors. Reliable anthropometric information on this development is available only for

about the last hundred years. During the last five decades stature has increased in North America and in Europe by about 1 cm per decade, on the average, while body weight has increased about 2 kg per decade. The reason is probably that improved nutrition and hygiene have allowed persons to achieve more of their genetically determined body-size potential. (If this explanation is correct, then the rate of increase should slowly taper off until a final body size is reached.) Data from Japan indicated initially a much faster average growth than found among Caucasians, but the rate seems to be slowing down now (Roebuck, Smith, and Raggio, 1988).

The most reliable data for observation of such secular trends are from military surveys. Measurements of U.S. soldiers have been minutely recorded since the Civil War. The military, however, is a selected sample of the general population, excluding, for example, people older than about 50 years, and people who are "unusual" in their body dimensions, such as extremely short or tall; also, only fairly healthy persons are included.

The anthropometric secular trends in 22 body dimensions of white, black, Hispanic, and Asian, female and male U.S. Army soldiers were investigated in 1990 by Greiner and Gordon. They found that some dimensions change only minimally, while others show fairly clear trends. The increases in stature and in sitting height seem to be slowing down: it now takes about 20 years before the gains are measurable with current techniques, by which time they are approximately another centimeter. Leg length (measured as crotch height), in contrast, is not changing appreciably. Yet, body weight is still increasing fairly fast, by 2 kg to 3 kg per decade. Shoulder breadth and chest circumference are increasing at rates of about 1 cm or more per decade. Altogether, white, black, and Hispanic U.S. Army soldiers show similar changes, while U.S. soldiers of Asian extraction exhibit quite different trends, which can be explained by recent immigration of Asians to the United States.

Population samples. Body dimensions of soldiers have long been of interest for a variety of reasons, among them the necessity to provide uniforms, armor, and equipment. Armies have medical personnel willing and capable to perform body measurements on large samples, available on command. Hence, anthropometric information about soldiers has a long history and is rather complete. For example, the anthropometric data bank of the U.S. Air Force Aerospace Medical Research Laboratory (CSERIAC) contains the data of approximately 100 surveys from many nations, though most on U.S. military personnel. Similarly, the "Human Biometry Data Bank-Ergodata" at the University René Descartes in Paris contains European anthropometric information.

Soldiers are certainly a subsample of the general population, but they are a biased sample because they are youngish, healthy, and neither extremely small nor big. Thus, their body dimensions may not truly represent the adult civilian population (although it appears that there are no major differences in head, hand, and foot

sizes). This problem was investigated by McConville, Robinette, and Churchill (1981). They selected several surveys done in the United States: for males, the 1965 HES (Health Examination Survey), the 1967 U.S. Air Force and the 1966 U.S. Army surveys; for females, the 1968 U.S. Air Force and 1977 U.S. Army surveys. Their underlying assumption was that if good pairing can be achieved in two "core" dimensions between civilian and military individuals, then the means and standard deviations of other dimensions should be well matched also. (This is a reasonable but arguable assumption.)

The procedure used was to match individuals from the civilian and military surveys on the basis of stature and weight, in intervals of plus-minus one inch and plus-minus five pounds. Thus, a new military sample was created which represented the civilians in height and weight. From this new matched military sample, dimensions other than height and weight were selected and compared to the equivalent data measured in the civilian surveys.

For the males (but not the females), an excellent fit was achieved: 99 percent of all civilian subjects could be matched with at least one military subject. The mean differences in stature and weight with regard to mean and standard deviation were nearly negligible. A comparison of six linear dimensions measured both in the military and civilian surveys provided similar good matches in means and standard deviations.

U.S. Civilians' Body Sizes

In earlier publications (e.g., Kroemer, 1981; Kroemer, Kroemer, and Kroemer-Elbert, 1986, 1990) the authors relied on *estimates* for the body dimensions of U.S. civilians based on data measured in the 1960s and 70s. In 1988, a thorough anthropometric survey of U.S. Army personnel was conducted (Gordon, Churchill, Clauser, Bradtmiller, McConville, Tebbetts, and Walker, 1989). In it, 2,208 female and 1,774 male soldiers were measured, who were subsets of soldiers sampled to match the proportions of age categories and racial/ethnic groups found in the active-duty army of June 1988. *Their anthropometric data are used in this book to represent the U.S. adult population.*

The decision to use these data was based on the following reasoning: among the U.S. military services, the Army is the largest and anthropometrically least biased sample of the total U.S. adult population. The measured sample in the 1988 survey is a mix of older and younger subjects: among the men, 30 percent were aged 31 and over, 25 percent between 25 and 30, and the others younger. Sixty-six percent were white, 26 percent black, 4 percent Hispanic, and the remaining 4 percent other racial/ethnic groups. Among the women, 22 percent were aged 31 and over, 32 percent between 25 and 30 years, and the others younger. Nearly 52 percent of the subjects were white, 42 black, 3 percent Hispanic, and 4 percent other racial/ethnic groups. Altogether, this survey is a reasonably good mix of ages and persons of various origins. Thus, the 1988 Army survey provides better information about the anthropometry of the civilian U.S. adult population than decade-old estimates.

We also compared specifically estimated civilian data, used previously, with those measured on the U.S. Army personnel. The largest absolute longitudinal differences were found in stature and sitting height, with the 1988 military population up to 2 cm taller. This appears to reflect the gains expected from the "secular" increase (discussed earlier) of about 1 cm per decade, but the majority of the data, particularly in widths and breadths, was similar in the two data sets. However, extremely heavy persons are more likely in the civilian population than in the army sample.

APPLICATION

Altogether, it is plausible that the 1988 U.S. Army survey constitutes, at present, the best estimate for the U.S. adult population. The 1988 data set contains 180 measurements (including 48 head and face dimensions) and 60 derived dimensions calculated from the measured data. The data are correlated in various ways. Thus, for information on data not reported here, the publication by Gordon, Churchill, Clauser et al. (1989) and the associated reports, listed there, should be consulted. Table 1-3 provides an excerpt of anthropometric data which should describe the adult U.S. civilian population well enough until better information becomes available.

NEED

Reliable information on body sizes of nonmilitary populations is missing—nationally and worldwide.

For standardization purposes, anthropometric measurements are done on persons standing or sitting erect with body joints at 0, 90, or 180 degrees—body postures not usually maintained at work. For the design of workstations and equipment, "functional" data are needed. Such data are often reported and used in engineering design guidelines (see, e.g., the sections on body posture, controls, and office design in this book), but they are dependent on stated or implied assumptions. A typical example is that of reach contours—see Figure 1-5.

Anthropometric Statistics

Fortunately, anthropometric data are usually distributed in a reasonably normal (or Gaussian) distribution (with the occasional exception of muscle-strength data). Hence, regular parametric statistics apply in most cases. The distribution of anthropometric information is, for practical purposes, well described by the *average* (mean), *standard deviation* SD, and *sample size* N. The *range* indicates extreme smallest to largest values.

TABLE 1-3. BODY DIMENSIONS OF U.S. CIVILIAN ADULTS, FEMALE/MALE, IN CM

	Percentiles			
	5th	50th	95th	SD
HEIGHTS				
(f above floor, s above seat)				
Stature ("height")^f	152.78 / 164.69	162.94 / 175.58	173.73 / 186.65	6.36 / 6.68
Eye height^f	141.52 / 152.82	151.61 / 163.39	162.13 / 174.29	6.25 / 6.57
Shoulder (acromial) height^f	124.09 / 134.16	133.36 / 144.25	143.20 / 154.56	5.79 / 6.20
Elbow height^f	92.63 / 99.52	99.79 / 107.25	107.40 / 115.28	4.48 / 4.81
Wrist height^f	72.79 / 77.79	79.03 / 84.65	85.51 / 91.52	3.86 / 4.15
Crotch height^f	70.02 / 76.44	77.14 / 83.72	84.58 / 91.64	4.41 / 4.62
Height (sitting)^s	79.53 / 85.45	85.20 / 91.39	91.02 / 97.19	3.49 / 3.56
Eye height (sitting)^s	68.46 / 73.50	73.87 / 79.20	79.43 / 84.80	3.32 / 3.42
Shoulder (acromial) height (sitting)^s	50.91 / 54.85	55.55 / 59.78	60.36 / 64.63	2.86 / 2.96
Elbow height (sitting)^s	17.57 / 18.41	22.05 / 23.06	26.44 / 27.37	2.68 / 2.72
Thigh height (sitting)^s	14.04 / 14.86	15.89 / 16.82	18.02 / 18.99	1.21 / 1.26
Knee height (sitting)^f	47.40 / 51.44	51.54 / 55.88	56.02 / 60.57	2.63 / 2.79
Popliteal height (sitting)^f	35.13 / 39.46	38.94 / 43.41	42.94 / 47.63	2.37 / 2.49
DEPTHS				
Forward (thumbtip) reach	67.67 / 73.92	73.46 / 80.08	79.67 / 86.70	3.64 / 3.92
Buttock-knee distance (sitting)	54.21 / 56.90	58.89 / 61.64	63.98 / 66.74	2.96 / 2.99
Buttock-popliteal distance (sitting)	44.00 / 45.81	48.17 / 50.04	52.77 / 54.55	2.66 / 2.66
Elbow-fingertip distance	40.62 / 44.79	44.29 / 48.40	48.25 / 52.42	2.34 / 2.33
Chest depth	20.86 / 20.96	23.94 / 24.32	27.78 / 28.04	2.11 / 2.15
BREADTHS				
Forearm-forearm breadth	41.47 / 47.74	46.85 / 54.61	52.84 / 62.06	3.47 / 4.36
Hip breadth (sitting)	34.25 / 32.87	38.45 / 36.68	43.22 / 41.16	2.72 / 2.52
HEAD DIMENSIONS				
Head circumference	52.25 / 54.27	54.62 / 56.77	57.05 / 59.35	1.46 / 1.54
Head breadth	13.66 / 14.31	14.44 / 15.17	15.27 / 16.08	0.49 / 0.54
Interpupillary breadth	5.66 / 5.88	6.23 / 6.47	6.85 / 7.10	0.36 / 0.37
FOOT DIMENSIONS				
Foot length	22.44 / 24.88	24.44 / 26.97	26.46 / 29.20	1.22 / 1.31
Foot breadth	8.16 / 9.23	8.97 / 10.06	9.78 / 10.95	0.49 / 0.53
Lateral malleolus height^f	5.23 / 5.84	6.06 / 6.71	6.97 / 7.64	0.53 / 0.55
HAND DIMENSIONS				
Circumference, metacarpale	17.25 / 19.85	18.62 / 21.38	20.03 / 23.03	0.85 / 0.97
Hand length	16.50 / 17.87	18.05 / 19.38	19.69 / 21.06	0.97 / 0.98
Hand breadth, metacarpale	7.34 / 8.36	7.94 / 9.04	8.56 / 9.76	0.38 / 0.42
Thumb breadth, interphalangeal	1.86 / 2.19	2.07 / 2.41	2.29 / 2.65	0.13 / 0.14
WEIGHT (in kg)	39.2* / 57.7*	62.01 / 78.49	84.8* / 99.3*	13.8* / 12.6*

*Estimated (from Kroemer, 1981).

Note: In this table, the entries in the 50th percentile column are actually "mean" (average) values. The 5th and 95th percentile values are from measured data, not calculated (except for weight). Thus, the values given may be slightly different from those obtained by subtracting 1.65 SD from the mean (50th percentile), or by adding 1.65 SD to it.

SOURCE: Adapted from U.S. Army data reported by Gordon, Churchill, Clauser, Bradtmiller, McConville, Tebbetts, and Walker (1989).

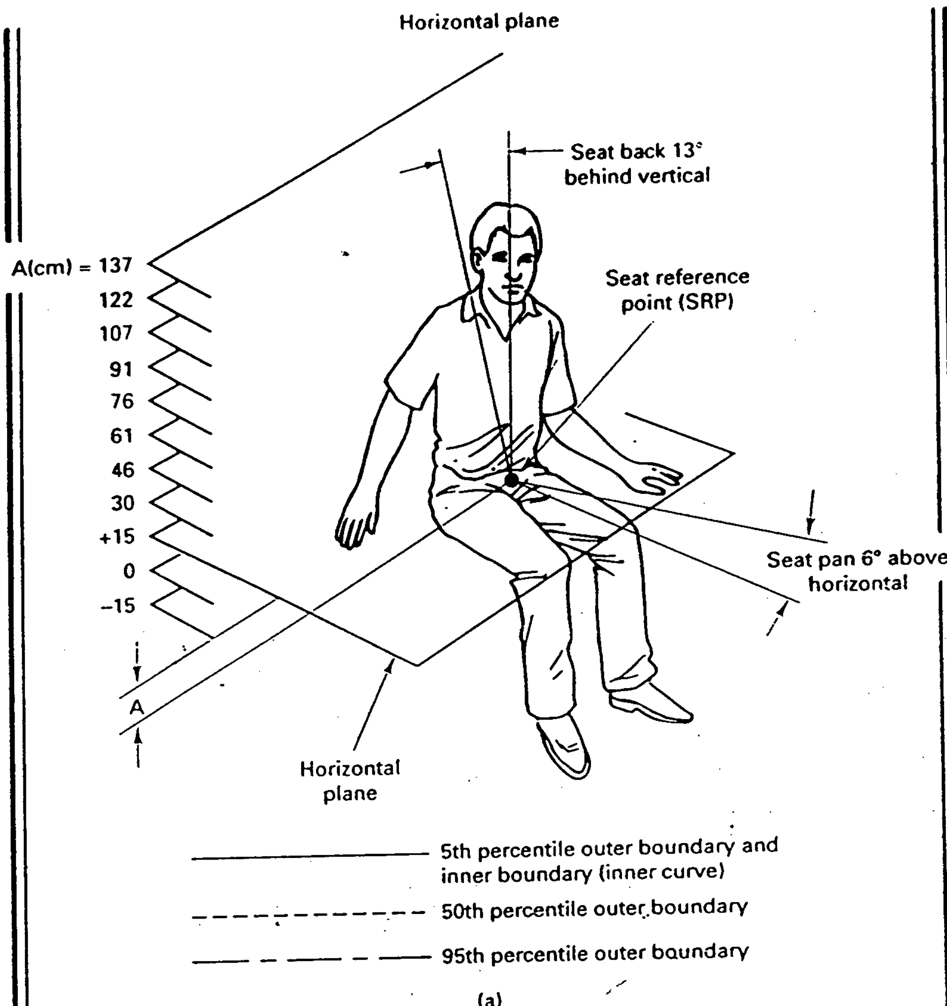


Figure 1-5(a). Definition of reach contours of U.S. Air Force males and females (adapted from NASA, 1989).

One easy way to check on data diversity is to divide the standard deviation of the data in question by their mean to get the *coefficient of variation,* CV. In most body dimensions, taken cross-sectionally, the CV is in the neighborhood of 5 percent; in most strength data, around 10 percent. Larger CV's are suspect and should prompt a thorough examination of the data.

Anthropometric data often are best presented in *percentiles.* They provide a convenient means of describing the range of body dimensions to be accommodated, making it easy to locate the percentile equivalent of a measured body dimension. Also, the use of percentiles avoids the misuse of the average in design (as discussed later).

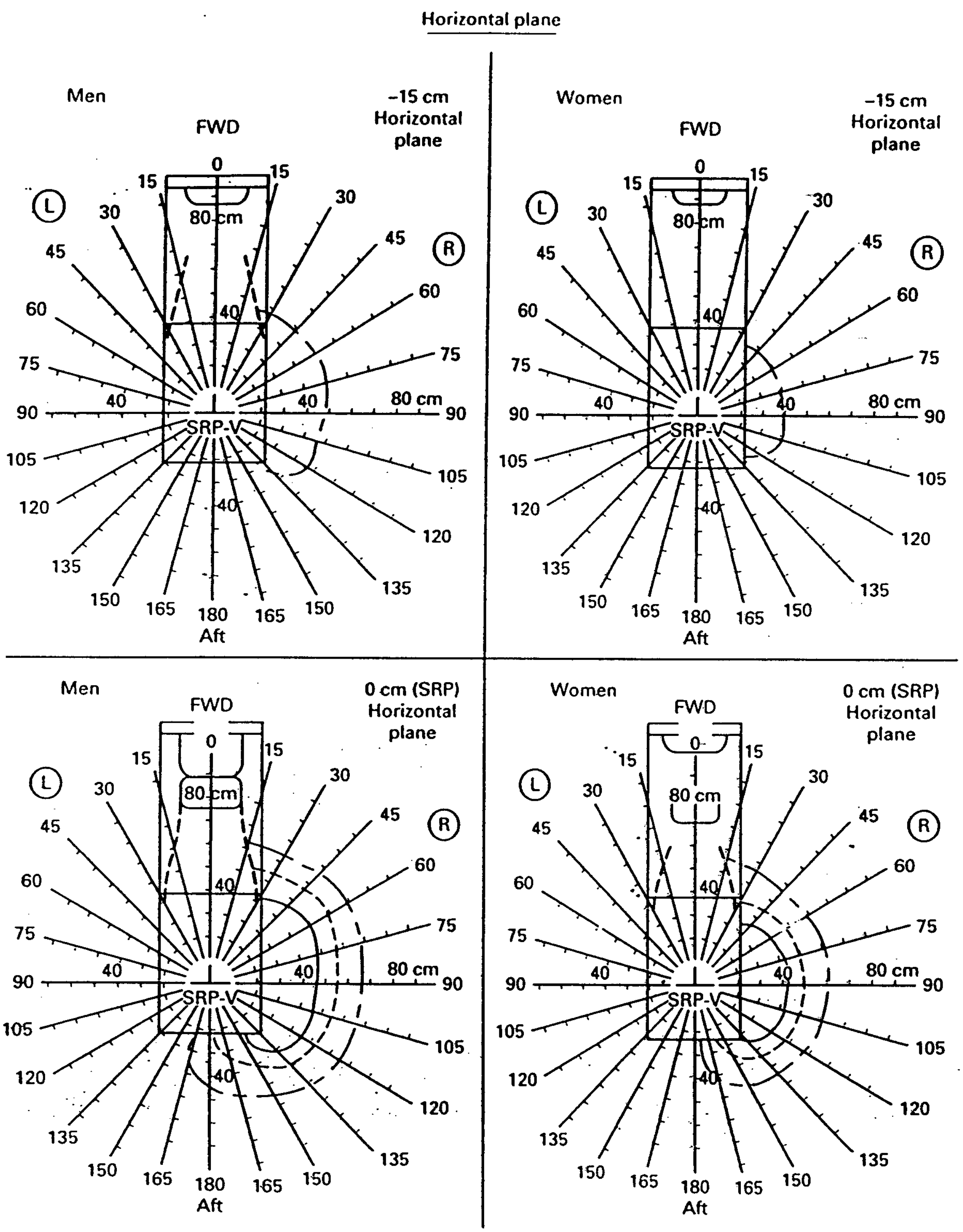


Figure 1-5(b). Reach contours in planes 15 cm below and at seat (SRP) height.

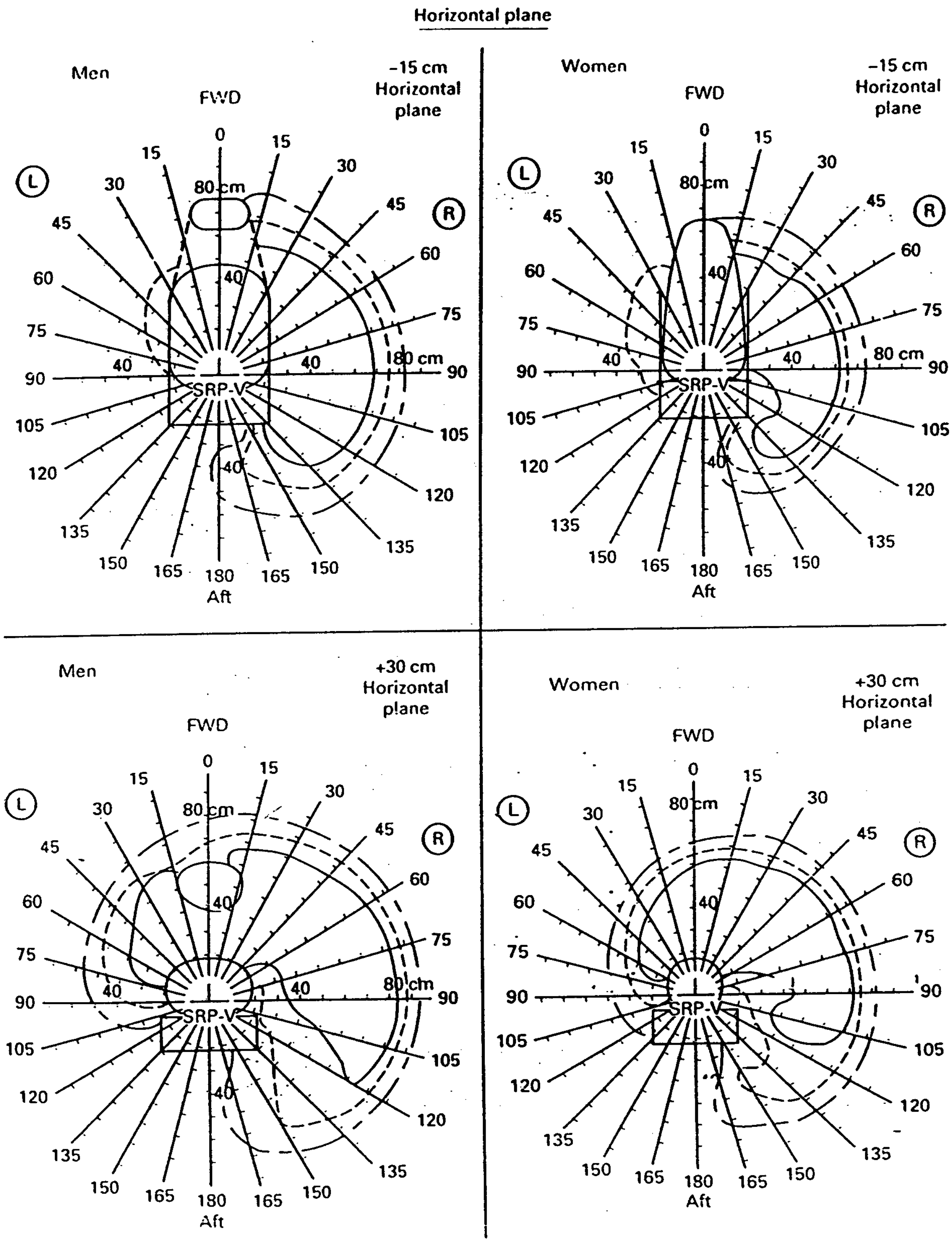


Figure 1-5(c). Reach contours in planes 15 and 30 cm above seat (SRP) height.

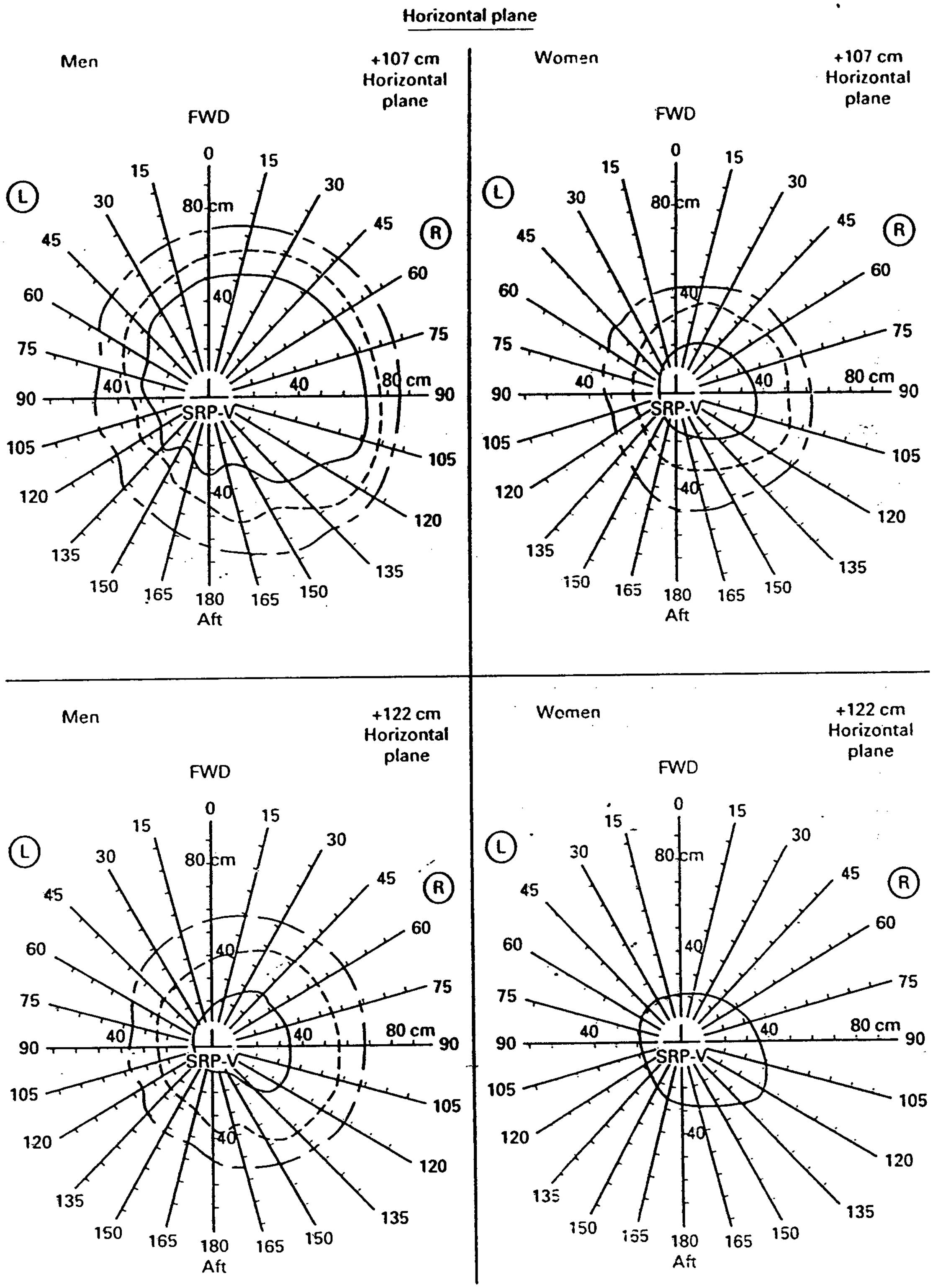


Figure 1-5(d). Reach contours in planes 107 and 122 cm above seat (SRP) height.

EXAMPLE

Percentiles serve the designer in several ways. First, they help to establish the portion of a user population that will be included in (or excluded from) a specific design solution. For example: a certain product may need to fit everybody who is taller than 5th percentile or smaller than 95th percentile in a specified dimension, such as grip size or arm reach. Thus, only the 5 percent having values smaller than 5th percentile, and the 5 percent having values larger than 5th percentile, will not be fitted. The central 90 percent of all users will be accommodated.

Second, percentiles are easily used to select subjects for fit tests. For example: if the product needs to be tested, persons having 5th or 95th percentile values in the critical dimensions can be employed for use tests.

Third, any body dimension, design value, or score of a subject can be exactly located. For example: a certain foot length can be described as a given percentile value of that dimension, or a certain seat height can be described as fitting a certain percentile value of popliteal height (a measure of lower leg length), or a test score can be described as being a certain percentile value.

Finally, the use of percentiles helps in the selection of persons to use a given product. For example: if a cockpit of an airplane is designed to fit 5th to 95th percentiles, one can select cockpit crews whose body measures are between the 5th and 95th percentile in the critical design dimensions.

For a normal distribution, percentiles are easily calculated from the mean and standard deviation. One need only multiply the standard deviation by a factor K, selected from Table 1-4, and then either deduct the result from the average to arrive at a certain percentile value below the 50th, or else add it to the average (which coincides with the 50th percentile) to arrive at a value above.

Body proportions. We often judge the human body by how body components "fit" together; our images of the beautiful body are affected by aesthetic codes, canons, and rules founded on often ancient (e.g., Egyptian, Greek, Roman) concepts of the human body. A more recent example is Leonardo da Vinci's drawing of the body within a frame of graduated circles and squares; it has been adopted, in simplified form, as the emblem of the U.S. Human Factors Society.

Categorization of body builds into different types is called *somatotyping*, from the Greek *soma* for body. Hippocrates developed, about 400 B.C., a scheme that included four body types, supposedly determined by their fluids. In 1921, the psychiatrist Ernst Kretschmer published a system of three body types intended to relate body build to personality traits ("Koerperbau and Charakter"). Kretschmer's typology consisted of the asthenic, pyknic, and ath-

TABLE 1-4. FACTOR K FOR COMPUTING PERCENTILES FROM MEAN $\bar{X}$ AND STANDARD DEVIATION S

	Percentile p associated with X	
K	$X = \bar{X} - KS$	$X = \bar{X} + KS$
2.576	00.5	99.5
2.326	1	99
2.06	2	98
1.96	2.5	97.5
1.88	3	97
1.65	5	95
1.28	10	90
1.04	15	85
1.00	16.5	83.5
0.84	20	80
0.67	25	75
0	50	50

Examples:
To determine 95th percentile, use $K = 1.65$.
To determine 20th percentile, use $K = 0.84$.

letic body builds. (The "athletic" type referred to character traits, not sports performance capabilities.) In the 1940s, the anthropologist W. H. Sheldon established a system of three body types, intended to describe (male) body proportions. Sheldon rated each person's appearance with respect to ecto-, endo-, and mesomorphic components—see Table 1-5. Sheldon's typology was originally based on intuitive assessment, not on actual body measurements; these were introduced into the system later by his disciples. Based on earlier research, Heath and Carter published in 1967 a revised procedure of somatotyping, which has been widely employed since.

Unfortunately, these and other attempts at somatotyping have not provided reliable predictors of human performance in technological systems. Hence, somatotyping is of little value for engineers or managers.

TABLE 1-5. BODY TYPOLOGIES

	Stocky, stout, soft, round	Strong, muscular, sturdy	Lean, slender, fragile
Kretschmer's terms	Pyknic	Athletic	Asthenic (leptosomic)
Sheldon's and Heath-Carter's terms	Endomorphic	Mesomorphic	Ectomorphic

Body image. *Body image* is a person's mental picture of the physical appearance of his/her body. This mental image affects lifestyle behaviors. Often, one's body image does not agree with the anatomical appearance: this results in *phantom body size*. In general, men tend to underestimate their sizes while women tend to overestimate. Even following much reduction of body weight, some individuals perceive themselves as having lost almost no weight: they still overestimate their body size. Anorexic patients often do this. On the other hand, some obese individuals who have lost weight tend to underestimate their body size. The extent of body-image distortion an individual has may be reflected in the likelihood of weight-regain (recidivism) after an initially successful weight-loss program: that probability is 75 to 95 percent after a quick weight reduction.

Anthropometric surveys in the United States and Europe have shown that short people tend to overestimate their stature, while heavy people often underestimate their weight. If one applies appropriate *multipliers* to counteract these tendencies, simply asking people (instead of measuring them, which takes more effort) for their height and weight can lead to fairly reliable information.

"Desirable" body weight? People who are severely overweight have a higher risk of health problems and of early death than their slimmer contemporaries. The more overweight, the higher the risk (National Institutes of Health, 1985).

Adipose (fat-containing) tissue is a normal part of the human body. It stores fat energy for use under metabolic demands. *Obesity* is an excess of such tissue. The reasons for obesity may be both behavioral and genetic. They include too much caloric intake, too little physical activity, and metabolic and endocrine malfunctions.

However, determination of a "healthy" or normal body weight is a difficult enterprise. Since there are no given cut-off points, any quantitative definition of normality or obesity is arbitrary. In 1985, a specially called committee of experts agreed that 20% or more above "desirable" body weight should be called obese. For that definition it is necessary to establish a desirable reference weight. Several methods are in use in the United States: "relative weight" is the measured body weight divided by the midpoint of the recommended weight (for "medium frame") in the 1983 Metropolitan Life Insurance Tables (Metropolitan Life Foundation, 1983). The 1990 USDA Weight Table (U.S. Dept. of Agriculture, 1990) uses the "body mass index," calculated by dividing the body weight (in kilograms) by the square of body height (stature, in meters). Of course, all these measures are only approximate, because body composition varies among individuals of the same height and weight (Andres, 1985; National Institutes of Health, 1985); in the general U.S. population, body weight correlates with stature only moderately.

APPLICATION

Correlations. Some body dimensions are closely related with each other. For example, stature is very highly correlated with eye height, but not with head length, waist circumference, or weight. Table 1-6 shows selected

TABLE 1-6. SELECTED CORRELATION COEFFICIENTS FOR ANTHROPOMETRIC DATA ON U.S. AIR FORCE PERSONNEL: WOMEN ABOVE THE DIAGONAL, MEN BELOW

	1	2	3	4	5	6	7	8	9	10
1. Age		.223	.048	−.023	.039	−.055	.091	−.072	.233	.287
2. Weight	.113		.533	.457	.497	.431	.481	.370	.835	.799
3. Stature	−.028	.515		.927	.914	.849	.801	.728	.334	.257
4. Chest height	−.028	.483	.949		.897	.862	.673	.731	.271	.183
5. Waist height	−.033	.422	.923	.930		.909	.607	.762	.308	.238
6. Crotch height	−.093	.359	.856	.866	.905		.467	.788	.264	.190
7. Sitting height	−.054	.457	.786	.681	.580	.453		.398	.312	.239
8. Popliteal height	−.102	.299	.841	.843	.883	.880	.485		.230	.172
9. Shoulder circumference	.091	.831	.318	.300	.261	.212	.291	.182		.810
10. Chest circumference	.259	.832	.240	.245	.203	.147	.171	.114	.822	
11. Waist circumference	.262	.856	.224	.212	.142	.132	.167	.068	.720	.804
12. Buttock circumference	.105	.922	.362	.334	.278	.217	.347	.149	.744	.766
13. Biacromial breadth	.003	.452	.378	.335	.339	.282	.349	.316	.555	.401
14. Waist breadth	.214	.852	.287	.260	.215	.195	.216	.133	.715	.801
15. Hip breadth	.105	.809	.414	.380	.342	.283	.376	.221	.632	.647
16. Head circumference	.110	.412	.294	.251	.233	.188	.287	.194	.327	.340
17. Head length	.054	.261	.249	.218	.208	.170	.244	.175	.201	.196
18. Head breadth	.122	.305	.133	.097	.089	.066	.132	.075	.245	.271
19. Face length	.119	.228	.275	.220	.226	.199	.253	.193	.162	.172
20. Face breadth	.233	.453	.190	.160	.142	.099	.185	.098	.401	.421

	11	12	13	14	15	16	17	18	19	20
1. Age	.234	.219	.149	.146	.194	.095	.118	.190	.189	.089
2. Weight	.824	.886	.495	.768	.770	.403	.304	.290	.264	.358
3. Stature	.279	.360	.456	.329	.348	.331	.318	.136	.267	.199
4. Chest height	.216	.289	.412	.266	.276	.284	.284	.085	.222	.162
5. Waist height	.238	.336	.409	.293	.318	.306	.297	.123	.225	.200
6. Crotch height	.221	.246	.380	.277	.225	.294	.280	.089	.205	.172
7. Sitting height	.236	.383	.384	.277	.379	.294	.275	.136	.248	.146
8. Popliteal height	.186	.201	.327	.249	.181	.235	.253	.087	.185	.189
9. Shoulder circumference	.775	.717	.581	.719	.606	.330	.248	.252	.217	.313
10. Chest circumference	.796	.674	.370	.706	.551	.273	.204	.255	.176	.273
11. Waist circumference		.722	.382	.886	.600	.281	.149	.267	.174	.310
12. Buttock circumference	.852		.396	.668	.893	.310	.214	.238	.180	.269
13. Baicromial breadth	.288	.355		.401	.361	.311	.239	.178	.266	.211
14. Waist breadth	.936	.849	.327		.576	.292	.168	.263	.182	.296
15. Hip breadth	.724	.895	.340	.760		.265	.183	.188	.155	.215
16. Head circumference	.309	.330	.251	.310	.288		.692	.430	.273	.299
17. Head length	.158	.195	.179	.164	.166	.779		.115	.311	.113
18. Head breadth	.265	.252	.188	.268	.227	.521	.058		.174	.497
19. Face length	.129	.186	.187	.151	.161	.315	.289	.148		.144
20. Face breadth	.412	.394	.278	.410	.364	.464	.131	.660	.206	

SOURCE: From NASA/Webb, 1978.

correlation coefficients among body dimensions of U.S. Air Force personnel, male and female. (More detailed tables are contained in publications by NASA/Webb, 1978; Cheverud, Gordon, Walker, Jacquish, Kohn, Moore, and Yamashita, 1990; and Kroemer, Kroemer, and Kroemer-Elbert, 1990.)

Given the varying correlations among body measures, the attempt is futile to express all body dimensions as a portion of stature. For several years a scheme was used by designers which supposedly expressed body heights, body breadths, and segment lengths in terms of fixed percent of stature. For instance, hip breadth was said to be 19.1 percent of height—misleading nonsense, of course, because hip breadth varies widely among individuals and between males and females as groups, and furthermore nothing can be designed for a fixed "average" hip breadth.

Some people say they weigh too much for their height. Others say they are too short for their weight. But there is little correlation between stature and weight.

A useful phenomenon is the correlation of certain anthropometric data with each other in such a way that as one increases, another (or several others) increases as well, or conversely, that as one increases, others decrease. In statistics this is called *covariation*.

The simple correlation coefficient r (also called Pearson product-moment correlation) is a measure of the strength of the linear relationship between two variables.

The correlation coefficient between the variables x and y can be defined as

$$r_{x,y} = \frac{\text{COV}(x, y)}{\sqrt{V_x V_y}} = \frac{\text{COV}(x, y)}{S_x S_y}.$$

where COV(x,y) is the covariance of x and y, and V their variance. The covariance measures the extent to which two variables vary in concert.

The covariance can be calculated from

$$\text{COV}(x, y) = \sum \frac{(x_i - \bar{x})(y_i - \bar{y})}{(N - 2)}.$$

The *variance* V measures the extent of differences among individuals in x and y. It can be calculated from

$$V_x = \sum \frac{(x_i - \bar{x})^2}{N - 1} \quad \text{and} \quad V_y = \sum \frac{(y_i - \bar{y})^2}{N - 1}$$

or

$$V_x = \overline{(x^2)} - (\bar{x})^2 \quad \text{and} \quad V_y = \overline{(y^2)} - (\bar{y})^2$$

where $\bar{x}$ and $\bar{y}$ are the averages (means) of the values of x and y, respectively; and $\overline{(x^2)}$ is the average of the squared values of x, and $\overline{(y^2)}$ the average of the squared values of y.

A *bivariate* regression expresses the linear relationship between a dependent variable y and a single independent variable x according to the equation

$$y = a + bx$$

with a the *intercept* and b the *slope*. They can be calculated from

$$b = \frac{\text{COV}\,(x, y)(N - 1)}{V_x(N - 2)} \qquad \text{and} \qquad a = \bar{y} - b\bar{x}$$

The *standard error of the estimate* for y, S_y, indicates the extent of variation in y for any given value of x. For large sample sizes N, a *95% confidence interval* for the estimated values of y can be calculated from

$$\bar{y} \pm 1.96S_y$$

meaning that 95% of all data fall within this range. (See Table 1-4 for other range factors.)

The coefficient of determination, R^2, measures the proportion of variation in the dependent variable y associated with the independent variable x, i.e., it measures the strength of association represented by the regression. R^2 is the square of the correlation coefficient between the two variables used in a bivariate regression equation, or among more variables in multiple regression equations.

It is common practice in engineering anthropometry (in fact in ergonomics altogether) to require a correlation coefficient of at least 0.7 as a basis for design decisions. The reason for this "0.7 convention" is that one should be able to explain at least 50 percent of the variance of the predicted value from the predictor variable: this requires r^2 to be at least 0.5, so r is at least 0.7075. (Note that r depends on sample size N.)

EXAMPLE

Clothing tariffs are examples of use, misuse, and non-use of correlations. In the United States, sizing of clothes for men is a fairly well organized and standardized procedure. Most men's jacket sizes run from "38" to "56", meaning that they should fit men with chest circumferences between 38 and 56 inches, in increments of one or two inches. Chest circumference, then, is used as the primary "predictor variable" for other design variables, such as coat length, shoulder width, and sleeve length. Similarly, trousers are ordered by waist circumference, and shirts by neck circumference.

In men's shirts, a given neck circumference is associated with a given chest circumference, while sleeve length may vary by one- or two-inch increments. This is an attempt to cover various body dimensions with a few shirt sizes, but it has obvious shortcomings: if a person needs a large neck size (e.g., size 17) such shirt also usually comes with ballooning chest and waist circumferences, which the buyer may not need. There is a trend to further con-

solidation of size ranges, providing shirts only in three neck sizes, "small," "medium," and "large," having only one sleeve length associated with each. Production variability is cut down very much in this simplified tariff, but fewer customers are fitted.

The situation for women's clothing is much less unified in the United States. There appears to exist only one ill-defined prototype "size 12" (based mostly on half-century-old data by O'Brian and Shelton, 1941), from which larger and smaller sizes are derived in nonstandard manners, as deemed suitable by each manufacturer. Hence, a woman well fitted by clothes of size 10 made by one producer may need a size 12, or 8, in clothing tailored by another company. This situation has allowed several manufacturers to become specialized in catering to "petite" or "mature" customers.

APPLICATION

How to Get Missing Data

Europe and North America have, anthropometrically, the best-known populations of the earth. Yet even here, the civilian populations are not assessed exactly, and current data on subgroups are sparse. The ergonomist may be interested in new information such as on Italians visiting swimming beaches (Coviglio, Fubini, Masali, Masiero, Pierlorenzi and Sagone, 1991), Irish workers (Gallery and Fitzgibbon, 1991), American farmers (Casey, 1989), pregnant American women (Culver and Vialo, 1990), U.S. hand sizes (Greiner, 1991), or Turkish schoolchildren (Vayis and Oezok, 1991). In many cases, the exact body dimensions needed for a design are not available in the literature.

Several routes exist to obtain the needed information. One is to actually measure a sufficiently large and well-selected sample of the population to be fitted. This is a time-consuming task, which should be done by anthropometrists or other specialists (although one can simply measure a few co-workers to get a rough estimate for the missing data). Another approach is to take the data of a population of known dimensions, if one has good reason to believe that population is similar to the one on which data are missing. (Yet: are Taiwanese similar in size to all Chinese?) In this case, it might also be highly advisable to seek help from an anthropologist or other well-informed person. The literature provides some help in discussing important aspects, such as sample selection, sample size, and composite populations (Chapanis, 1975; Kroemer, Kroemer, and Kroemer-Elbert, 1990; Lohman, Roche, and Martorell, 1988; Pheasant, 1986).

A rather interesting task is the prediction of future body dimensions, which are needed when equipment must be designed for use in decades to come. In the 1960s, for example, NASA was concerned about the body sizes of

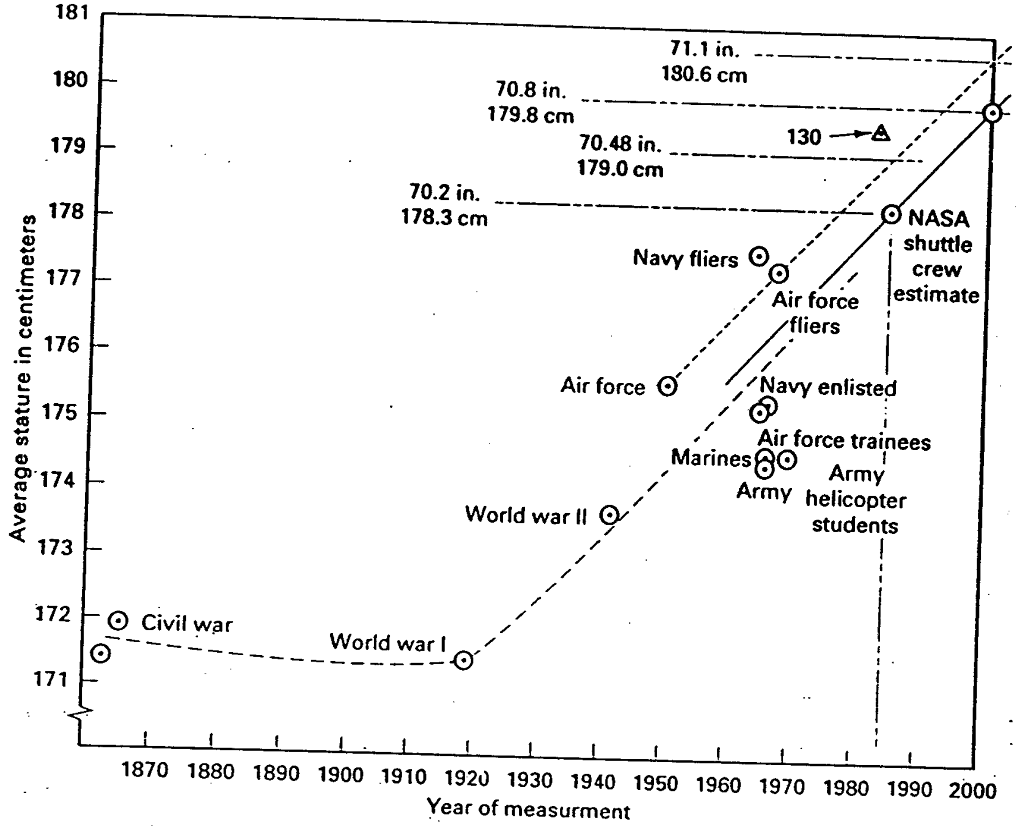


Figure 1-6. Predicted average stature for USAF and NASA male flying personnel (with permission from Roebuck, Smith, and Raggio, 1988).

astronauts in the 1980s and 90s. In 1988, Roebuck, Smith, and Raggio used a large variety of sources, military and civilian, U.S. and foreign, together with regression equations to forecast the body dimensions of astronauts in the year 2000. Figure 1-6 shows their predicted values for male U.S. Air Force and NASA flight crews in terms of stature. Figure 1-7 shows their predictions for American and Asian women.

Phantoms, Ghosts, and the "Average Person" Homunculus

Several misleadingly simple body-proportion templates have been used in the past (e.g., Drillis and Contini, 1966). In fact, all "fixed" design templates fall in that category, if they assume that all body dimensions, such as lengths, breadths, and circumferences, can be represented as given fixed proportions (percentages) of one body dimension, for example, stature. Obviously, such a simplistic assumption contradicts reality: the relationships among body dimensions are neither necessarily linear, nor the same for all persons. In spite of the obvious fallacy of the model, "single-percentile constructs" have been gener-

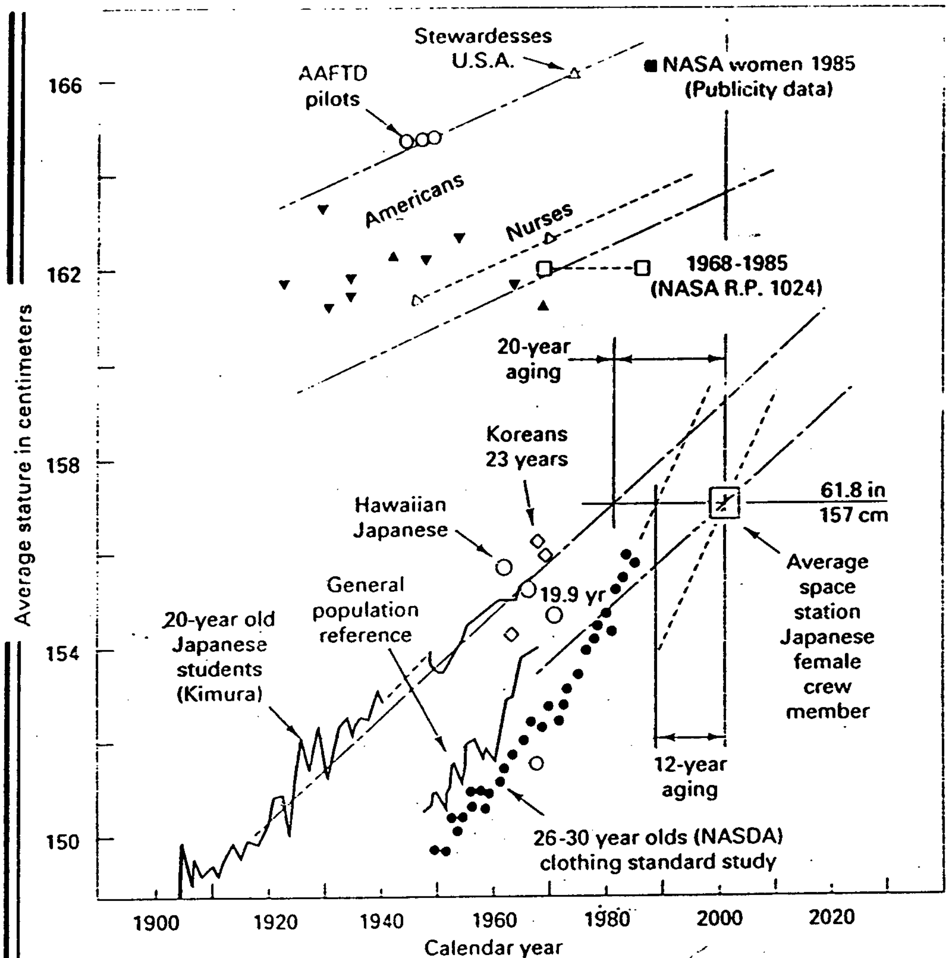


Figure 1-7. Predicted average stature for American and Asian women space crews (with permission from Roebuck, Smith, and Raggio, 1988).

ated, assuming that homunculi exist whose body segments are all of the same percentile value. Not only the 50th-percentile phantom (the "average person") has been used as a design template, but other ghostly figures have been created that have, for example, all 5th- or 95th-percentile values. Of course, designs for these figments do not fit actual users.

"Fitting" Design Procedures

Information about body size is needed when an object must fit the human body, such as tool handles to hold, protective equipment and clothing to wear, chairs to sit on, windows to look through, and workstations in general. Several of

these applications are discussed elsewhere in this book (see, for example, the sections on hand tools and computer workstations). Different fitting methods are used, such as choosing exact percentiles on the continuum of the measuring scale to determine ranges (say, from 5th to 67th percentile) or to assure that the largest persons will fit through an opening, or that even the smallest can use the equipment. In this context, one often speaks of "functional" (or dynamic) anthropometry, meaning body data that depend on the coordinated efforts of several body segments to achieve a desired posture or perform an activity. These may define zones of convenience, of expediency, of minimally required or largest covered space.

Zones of convenience or expediency are difficult to define because the criterion is not absolute (in the sense of minimal or maximal) but depends on the situation, the subject, the task. The various "normal working areas" first shown in the 1940s, usually in form of partial spheres around the elbow or shoulder, are examples of plausible yet ill-defined convenience contours. It is difficult to accept that a male person should have a working area within a "radius of 394 mm from the shoulder," while a female worker should have a working area limited by a "radius of 356 mm" (Nicholson, 1991): why those exact dimensions? Of course, it makes sense that work should be done within easy reach—see Figure 1-8—one just has to define what "easy" means.

An example of a clear and defined procedure is the determination of "safe distance from a danger point." The danger point is that edge of a hazardous gadget (such as of a press mold, cutting edge, or pinch point) closest to the operator from which the operator's body (usually the finger or toe) must be kept. The safe distance is the straight line distance between the danger point and the barrier (wall, safety guard, enclosure of an opening) beyond which the operator's body cannot proceed toward the hazard. That distance should be increased by a safety margin.

For finger safety, the distance may be determined either past an opening which allows only the finger to penetrate; or past an opening or barrier which can be overreached by the arm. In the first case, the safe distance would be the length of the longest possible finger, with a safety margin; in the second case, the distance would be determined by the longest arm and finger reach.

For foot safety, the most likely barrier is at the ankle, so that only the toes and foot can penetrate further toward the danger point; or the whole leg may have to be considered, probably restrained in the hip area.

There are many variations of these conditions, such as those in the German Standard DIN 31001 and the British Standard BS 5304. Some of these conditions are shown in Figure 1-9.

In each case, the longest possible body segment should be considered, under the given conditions of barrier and mobility. A predetermined safety margin (of, say, 10 percent) should be applied to those body lengths. Certain conditions, such as holding an object that, if entrapped, might pull the hand to-

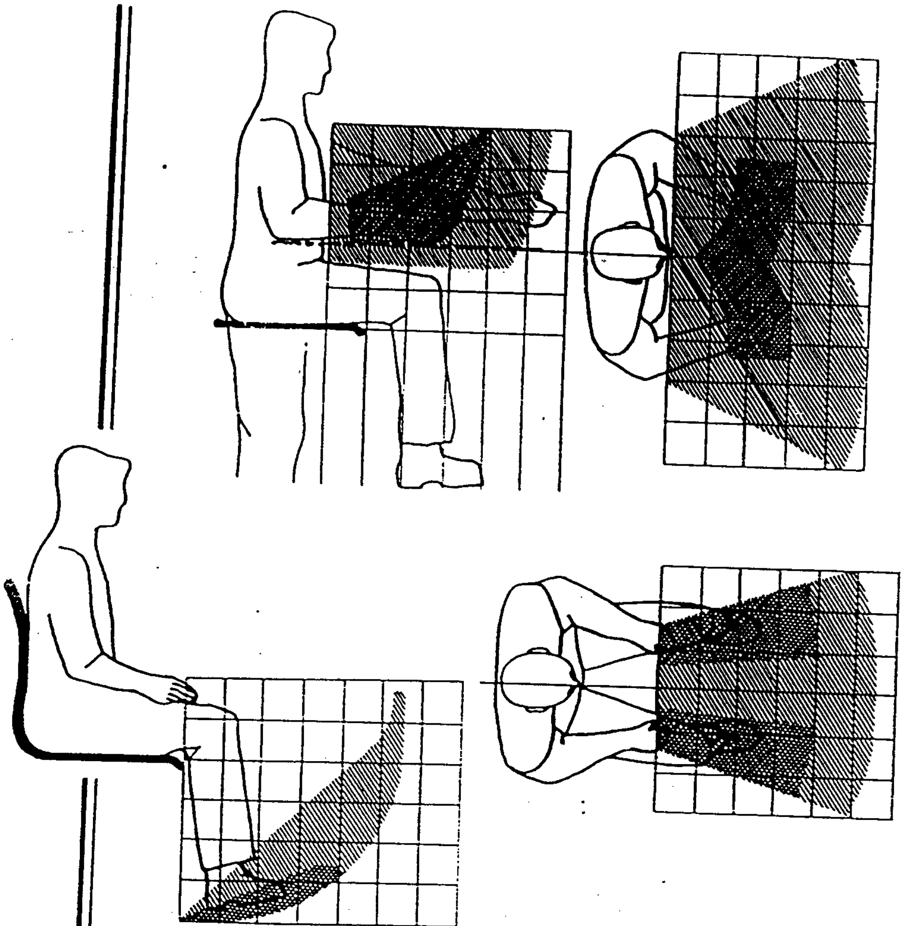


Figure 1-8. The concept of "preferred" working zones of the hands and feet.

ward the hazard point, could be good reason to extend the safety distance further.

A similar strategy should be applied when workstations, tools, and tasks must be designed for small operators. The needs to see, to reach, to apply force are derived from the smallest operators, yet these criteria may not accommodate large persons. Possible solutions would be to have adjustable object dimensions, or to have objects in different sizes (Ayoub and Miller, 1991; Bottoms and Butterworth, 1990; Buckle and David, 1989; Pheasant, 1986; Nicholson, 1991; Thompson, 1989).

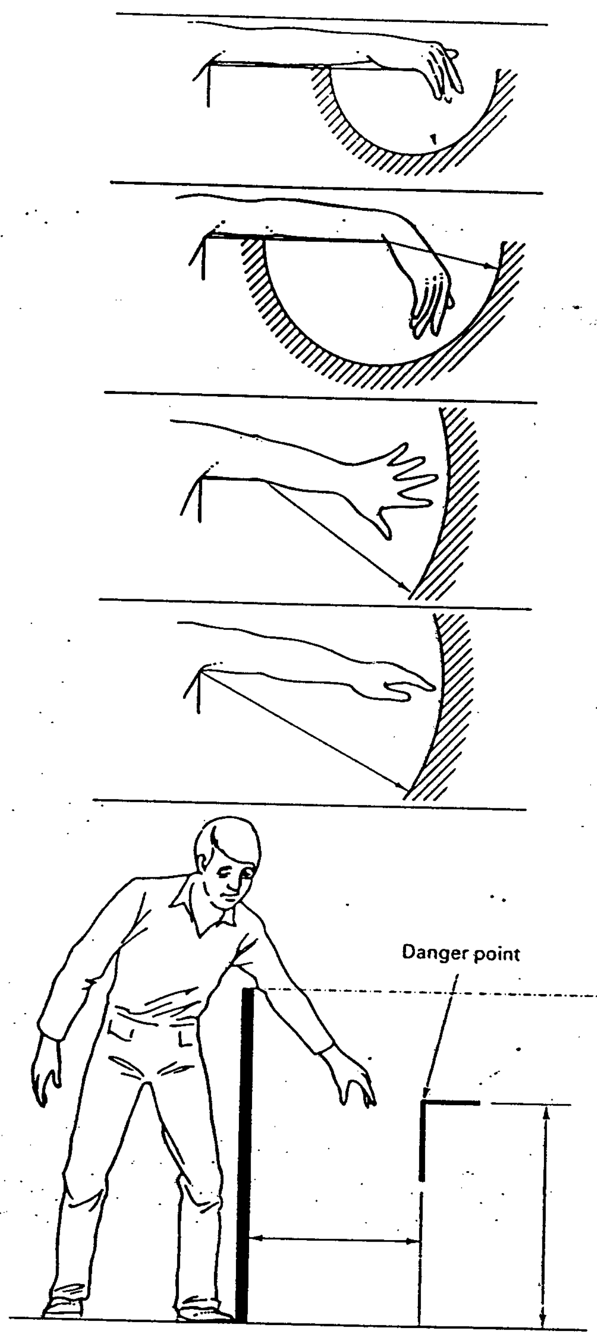


Figure 1-9. Examples for "safe distances" (modified from DIN 31001 and BS 5304).

For a standing operator, some "toe space" should be provided so that one can step close to the workstation. This space should be high enough to accommodate persons wearing thick soles, but shallow enough so that one does not hit the edge of the foot-space cutout with the instep of the foot. Thus, a depth not to exceed 10 centimeters, and a height of not less than about 10 centimeters should be appropriate—see Figure 1-10.

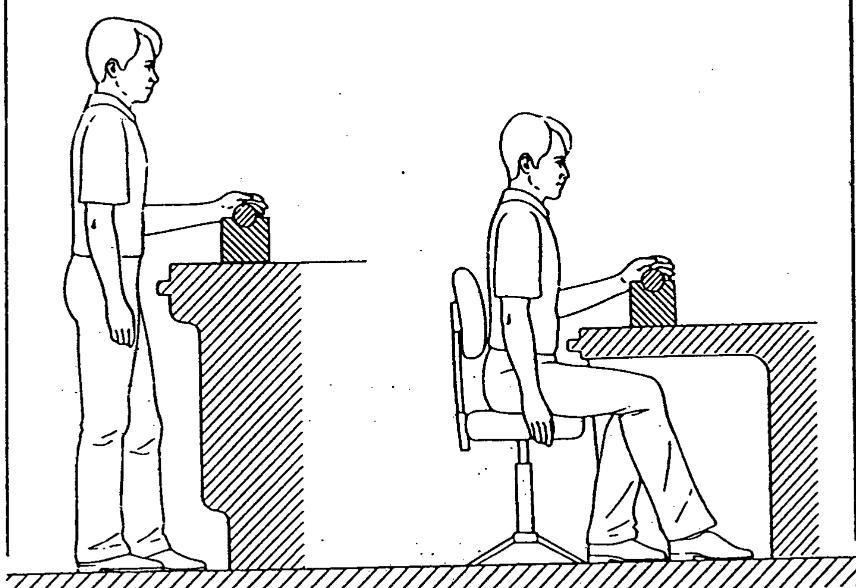


Figure 1-10. Shape of workstations at which the operator stands or sits.

Then, the height of the work surface must be determined. That depends on the physical work to be performed, on the dimensions of the workpiece itself, and on the need to observe the work done. As a general rule, the manipulation itself should be performed at about the height of the elbow of the operator when the upper arm hangs down along side the trunk, or is slightly elevated forward and sideways. For example: Table 1-3 shows an elbow height of about 93 cm for a 5th-percentile standing female operator, and 107 cm for a 95th-percentile standing female. For standing male operators, the respective elbow heights are 100 and 115 cm. One may reduce these heights if the operator does not stand "erect," but that may be offset by the heel height of shoes worn. If the workpiece is large, and the manipulation is performed on its upper part, the support surface (bench height) must be low enough to allow the hands to be at elbow level. However, the work might need close visual observation; this requires an appropriate viewing distance. In that case, particularly if the manipu-

lation requires fairly little force and energy, the work area might be elevated well above elbow height. (But that, in turn, might require support for the elevated hands and forearms.) These conditions are illustrated in Figure 1-10.

To determine actual design values for the workstation, the relevant body dimensions (in particular, elbow height and eye height) of the expected operator population must be selected, and adjusted according to body postures and specific work requirements. For a sitting operator, the elbow height will not be referenced to the floor but to the height of the seat surface. For example: the elbow height of a sitting person is given in Table 1-3 as 18 and 26 cm for the 5th- and 95th-percentile female, respectively; and as 18 and 27 cm for male operators. However, the support surface can be lowered only until it nearly touches the upper side of the thighs: the thigh height in Table 1-3 ranges from 14 cm to 19 cm above the seat height for the 5th- to 95th-percentile operator, whether female or male. These values establish the necessary height of the space underneath the working surface to accommodate the legs of the sitting operator. Another way to determine the needed height of the leg space is to use the "knee height," also given in Table 1-3, plus some allowance for shoe heels.

The width of the leg room is not critical if it exceeds the hip width of the widest operator. The depth of the leg room should exceed the largest distance from the front of the belly to the kneecaps. This is not a dimension customarily measured by anthropometrists; it has to be estimated. A deep leg space is desirable, so that one can extend the lower legs and push the feet forward. The height of the work seat should be adjustable to fit persons with long and short lower legs. This adjustment is best achieved by varying the height of the seat surface (as discussed in more detail in Chapter 9 on office design).

Occasionally, one is called upon to design a workstation at which the operator could either sit or stand. This task in essence combines the major requirements of the stations for either sitting or standing. Specifically, there must be a very tall chair, and a high support surface for the feet. A small board or bar attached to the chair is not recommended, because it reduces the stability of the chair while providing little support surface for the feet, which, accordingly must be kept in place, often by muscle tension instead of being able to move to different positions. The general principles for a combined sit-stand workstation are sketched in Figure 1-11.

Design procedures. Proper procedures are available to develop analogs of the human body (Kroemer, 1989). The "subgroup" method creates models that represent the extreme ends of the body-size range. One identifies critical dimensions and assures that they are fitted. If both the smallest and the largest are taken, one is fairly sure that the intermediate range is accommodated. As Haslegrave (1986) explains, this can be relatively simple, particularly if the problem is one-dimensional or there are no relationships among several relevant dimensions.

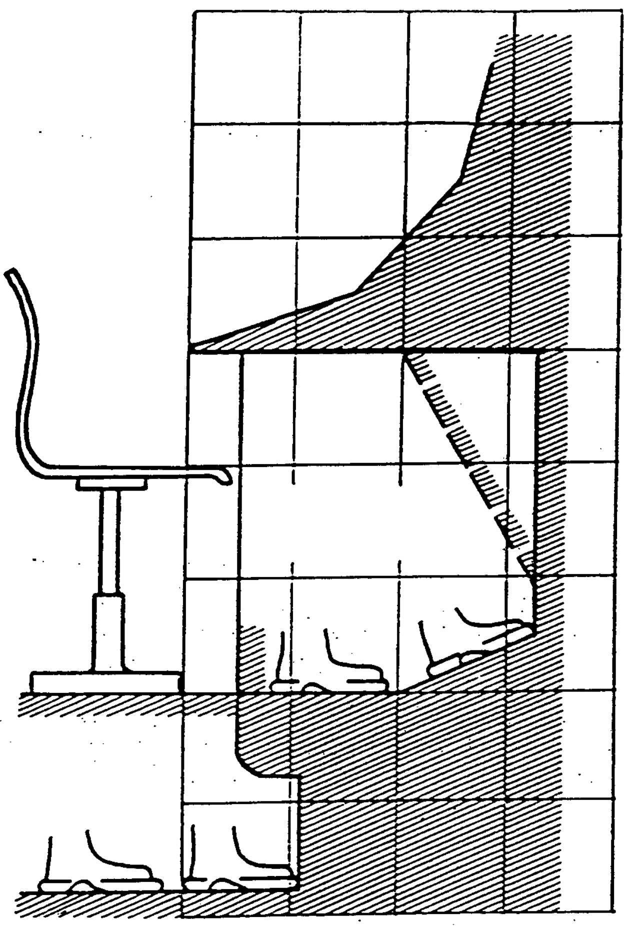


Figure 1-11. Workstation for standing or sitting, or for alternately sitting and standing operation.

If one "stacks" values of a given percentile, such as the 5th, one does not end up with a composite figure that, in its sum, is also 5th percentile. For example: 5p hip height plus 5p trunk height plus 5p head height do NOT add up to 5p stature.

A combination often used to determine an *n*th-percentile person is that of stature and weight (as in "desirable" weight-height ratios). Yet, the correlation between the two values is low, in the neighborhood of 0.3 for women and 0.4 for men in the general population. Haslegrave concluded that the best way to

present a 5p woman (or a 5p man) is to measure a group of women (or men) who have this stature and weight, and to calculate from their measures the median values of all other dimensions of interest in the group. If one then checks each resulting value, this is likely not to be exactly at the 5th (or 95th) percentile, but close to it. An alternative is to use regression equations. The major advantage of the regression-based procedure is that the resulting values are additive, which percentile values are not (McConville and Churchill, 1976; McConville, Robinette, and Churchill, 1981).

A useful and correct general design procedure (Kroemer, Kroemer, and Kroemer-Elbert, 1986, 1991, and Pheasant, 1986) entails four steps, as follows:

Step 1: *Select those anthropometric measures that directly relate to defined design dimensions.* Examples are: hand length related to handle size; shoulder and hip breadth related to escape-hatch diameter; head length and breadth related to helmet size; eye height related to the heights of windows and displays; knee height and hip breadth related to the leg room in a console.

Step 2: *For each of these pairings, determine whether the design must fit only one given percentile of the body dimension, or a range along that body dimension.* Examples are: the escape hatch must be fitted to the largest extreme values of shoulder breadth and hip breadth, considering clothing and equipment worn; handle size of pliers is probably selected to fit a smallish hand; the leg room of a console must accommodate the tallest knee heights; the height of a seat should be adjustable to fit persons with short and with long lower legs. (Table 1-4 shows how to calculate percentile values.)

Step 3: *Combine all selected design values in a careful drawing, mock-up, or computer model to ascertain that they are compatible.* For example: the required leg-room clearance height, needed for sitting persons with long lower legs, may be very close to the height of the working surface, determined from elbow height.

Step 4: *Determine whether one design will fit all users.* If not, several sizes or an adjustment must be provided to fit all users. Examples are: one large bed size fits all sleepers; gloves and shoes must come in different sizes; seat heights are adjustable.

The following appeared in the Washington Post *of May 25, 1984:*

The Navy has adopted new flight training standards that will require its aviators, as a whole, to have longer arms and shorter legs. The standards will exclude 73 percent of all college-age women and 13 percent of the college-age men, according to a military spokesman. [He] said the new standards were devised because some avia-

tion candidates could not reach rudder pedals or see over instrument panels. Some taller pilots were so tightly wedged that their helmets bumped the aircrafts' canopies. "We found out that manufacturers are still building airplanes the way they want, but God is not making people to fit them." Previously, 39 percent of the female applicants and 7 percent of the men were ineligible to become aviation candidates because of their size.

Six years later, the cockpit dimensions of aircraft used throughout the world (Boeing 737-200, 747, 757, and Lockheed TriStar) were evaluated with respect to eight critical body dimensions of pilots, including eye height, hand and leg sizes, and reaches. In many cases, the fit was marginal, at best. For example, based on eye height, 13 percent of the British male and 73 percent of the female pilot candidates would have to be excluded from being crew members (Buckle, David, and Kimber, 1990).

HUMAN BIOMECHANICS

In biomechanics, one attempts to understand characteristics of the human body in mechanical terms. The biomechanical approach is not new. Biomechanics has been applied to the statics and dynamics of the human body, to explain effects of vibrations and impacts, to explore characteristics of the spinal column, and to the use of prosthetic devices, to mention just a few examples.

Leonardo da Vinci (1452–1519) and Giovanni Alfonso Borelli (1608–1679) combined mechanical with anatomical and physiological explanations to describe the functioning of the biological body. Since Borelli, the human body has often been modeled as consisting of long bones (links) that are connected in the articulations (joints), powered by muscles that bridge the articulations. The physical laws developed by Isaac Newton (1642–1727) explained the effects of external impulses applied to the human body.

Treating the human body as a mechanical system entails gross simplifications, such as disregarding mental functions. Still, many components of the body may be well considered in terms of analogies, such as:

bones—lever arms, central axes, structural members

articulations—joints and bearing surfaces

tendons—cables transmitting muscle forces

tendon sheaths—pulleys and sliding surfaces

flesh—volumes, masses

body contours—surfaces of geometric bodies

Tuesday, 28 March 2000

Application 2: Footwear and Clothes Design
by Ravindra Goonetilleke

Effective Anthropometry Process
by Kathleen Robinette

Statistics for Anthropometry
by Kathleen Robinette

Anthropometric Fit Mapping
by Kathleen Robinette

Application 3: Crew Station Design
by Kathleen Robinette

The Quality of Footwear Fit: What we know, don't know and should know

Ravindra S. Goonetilleke+, Ameersing Luximon, and Kwok L. Tsui
Department of Industrial Engineering and Engineering Management
Hong Kong University of Science and Technology
Clear Water Bay, Hong Kong
+Email: ravindra @ust.hk

Even though fit ranks as one of the most important considerations in the purchase of a shoe, the quality of fit has no metric and is hence poorly assessed. Manufacturers, retailers, and customers tend to use trial and error techniques to improve footwear fit. This approach is rather cumbersome and very unscientific. In this paper, we present a methodology to assess and thereby quantify footwear fit so that comfort can be predicted and consequently improved lasts and shoes can be produced that match different shapes of feet.

INTRODUCTION

The Japanese Industrial Standard JIS Z 8101-1981 ines quality as the totality of the characteristics and performance that can be used to determine whether or not a product or service fulfills its intended application. Product uality is generally evaluated on the basis of whether or not he product carries out its intended functions and the extent to which a product meets the requirements of the user. Monitoring and correcting whether the product meets its ntended functions are aspects that have been extensively discussed in the quality literature. However, the same is not true in the "buying process modification" when a product loes not meet the user's perceived requirements. This is especially the case when human body parts need to match with the product components or characteristics. The primary problem in all such cases is the lack of an evaluation metric(s).

Product performance can be broadly evaluated based on its *function* (that is the product works as designed), *form* appealing to the eye), and *fit* ("matches" the purpose). In many cases, fit can govern function and is hence an important property. In traditional mechanical engineering lications, there are different types of fit depending on unction. For example, a bearing requires an interference fit on a shaft. In this case, the difference between the shaft diameter and the internal diameter of the bearing has to be vithin a given tolerance in order to produce the required nterference fit. In applications involving people, on the other hand, fit is generally not well defined. A good example is shoe fit. Clinical reports of foot problems such s blistering, chafing, black toes, bunions, pain, and tired feet are evidence of poor fitting shoes. Footwear fit has been understood to mean the preference for a shoe to ccommodate an individual's foot. As Kolarik (1995, pp. 41) tates, "... a customer may demand shoes that fit right (a "true" quality characteristic). The customer will judge his or her shoe fit by wearing the shoes ...".

THE RIGHT FIT

When the foot-shoe "tightness" exceeds a certain hreshold, discomfort or pain results. The discomfort hypothesis that was proposed by Goonetilleke (1998) could be used to delineate the phase change between comfort and discomfort if the threshold for the complete surface of the foot is known. In other words, quantification of fit will allow for the prediction of discomfort and pain. Such quantifications can save time and money in reducing the lengthy fit testing that is normally performed when prototype shoes are made.

If the shoe is "loose" on the foot, it is generally not as uncomfortable (even though function may be impaired) as when it is tight. In either case, the acceptable looseness/tightness is subjective and rarely quantified. Worst of all, the customer cannot predict the "fit-drift" and the bearability or even acceptability of the shoe-foot fit in the long term.

Ergonomists have been striving to achieve the right fit between people and the tools or equipment they use, but this so called "right fit" or compatibility is generally unknown in many circumstances (Karwowski and Jamaldin, 1996). Footwear manufacturers have not designed or developed a true quality characteristic to evaluate the fit between a person's foot and the footwear he or she wears. As Kolarik (1995) pointed out, the customer evaluates the quality of fit by *wearing* the shoe. The perceived fit depends on many factors. Some of which are time of day, activity performed, a person's health status, and so forth. As a result, footwear purchased at some time on some day may not fit as well on a different day or throughout the complete day. The size variations of feet are always an excuse to avoid quantifying the fit between shoes and feet. However, from a quality control point of view, it is always more informative to use a quantitative measure to evaluate the fit of footwear, even when foot size variations are present. In terms of statistical process control (SPC), the foot size variation can be considered as a common cause variation and the shoe size misfit can be considered as a special cause variation. Similar to SPC problems, it may be possible to use control chart methods to quantify the foot size variation, to identify the shoe size misfit, and to track the shoe deformation. It will be interesting to modify the current SPC methods to develop appropriate tools for monitoring foot size and shoe size variations to improve the quality of footwear fit.

The stated fit-problem is exacerbated when selecting children's shoes. An adult, who may press on the toe area to get an indication of the available toe space, evaluates the fit of

a child's shoe. How acceptable is such a fit? Is length the only critical measure for footwear fit? Most fit problems are generally around the "width" dimension since the commonly used shoe sizing system is predominantly in the length dimension. How much do we know about this "width" dimension? Pain or discomfort in the ball area of the foot (metatarsophalangeal joint area) is almost always associated with a narrow shoe. At the same time, people find good-fitting shoes that are sleek and narrow. How could this happen? The objective of this paper is to explain such misconceptions related to footwear fit and how they can be overcome using a quantitative measure of fit.

What we know

Even though no one may really care, our shoes generally wear on the outside part of the heel whereas the slippers we use show wear on the inside part (medial) of the heel. If the wear is to be uniform in the heel area, then one alternative is to make the outside part of the heel of a shoe and the inside part of the heel of a slipper with a material having good wear properties. Footwear manufacturers adopt this "doctor" approach of "treating the symptoms" without caring about the underlying cause of such symptoms. The reasons for the difference in wear can be explained using the concept of flare and the concept of "holding" or "clamping". This concept of "holding" is critical in the development of the fit metric.

Another important fact is that we need to break-in new shoes for quite some time before they can be worn without any discomfort. In engineering applications, the break-in period is meant to take care of "surface imperfections" and to minimize seizure as a result of close-fitting parts. With new shoes, the break-in period is intended to deform the upper material to fit the shape of the foot. During the break-in period, we expect the shoe to "mold" to the shape of the foot. Any material resistance to this change results in discomfort or pain. If the material is soft and flexible, the shoe will lose its shape and if the material is reinforced and rigid, discomfort will result if the foot-shoe fit is not proper. Either one of the two options is not suitable. What is the cause(s) for such a misfit even when a shoe has been sized to the correct length?

A shoe (and the last or shoe mold) is characterized by its longitudinal "curvature" as being "straight" or curved (Cavanagh, 1980; Cheskin, 1987). On some shoe (and last) bottoms, the longitudinal centerline is relatively straight, making it sometimes difficult to distinguish the left and right sides (Figure 1). On others, known as *curved*, *racing* or *inflared* lasts, there exists a distinct inward turn towards the medial side of the foot (Figure 1). The term curved last is a misnomer since in reality it is a piecewise linear centerline (Goonetilleke and Luximon, in press). The amount of turn is characterized using a measure called *flare*. Today, identical left and right shoes are rarely seen even though they were common in the 19th century. Most shoes have a 6-degree (Holscher and Hu, 1976) or 7 degree (Cheskin, 1987) flare angle. The origin of the curved last (or shoe) was based on the writings of Meyer (1860) who suggested that the straight lasted shoe did not fit the curved foot and was a major cause of foot problems. Have human feet remained the same over the last century or more even though Cheskin (1987) also *claimed*, without any formal proof, that most feet have a slight inward curve? Even so, many researchers have argued the necessity for straight lasts (Holscher and Hu, 1976; Rossi, 1988). Hence, we need to question whether shoe manufacturers have taken Meyer's concept to the extreme, thereby exacerbating foot problems due to a mismatched flare. The popularity of inflared lasts may be due to the fact that the foot actually has a significant flare, or it may reflect an aesthetic consideration in favor of a longer first toe such that each shoe has a built-in medio-lateral symmetry rather than a longer medial side.

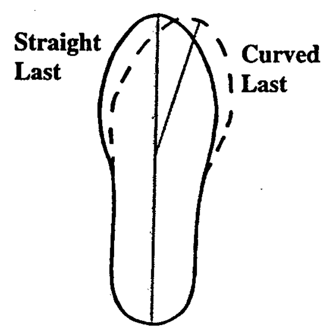
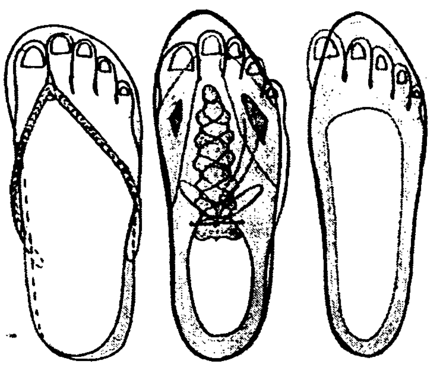


Figure 1. Straight and Curve lasts

In ergonomics, "neutral posture" is claimed to be essential to minimize overuse injuries (Putz-Anderson, 1988). An excessive flare or an insufficient flare in footwear will result in deviations from neutral postures. Thus, the neutral alignment that the foot seeks may be altered by an incongruous shoe resulting in the impairment of stability, strength and potential injury. It is interesting to note that fitting footwear (ANSI/ASTM F539-78, 1986) concentrates predominantly on two areas: the toes and the metatarsal region (ball joint). The foot measuring devices such as the Brannock, Ritz stick, and Scholl have also concentrated on these two areas by measuring the length along the foot and the maximum width at around the metatarsophalangeal joint area. It is therefore not surprising that different models of shoes fit differently because of the inflare built into them.

The only reference to flare can be found in the British Standard (BS) 5943 (1980) in relation to orthopedic footwear. The British Standard emphasizes the need for forefoot alignment. However, that description is somewhat inadequate. It indicates that the foot alignment needs to be checked in the plan view by making sure that there is no centrally directed pressure on the first toe (big) and the smallest (5th) toe. In other words this standard is a recommendation to check the flare matches between shoes and feet.



(a) (b) (c)

igure 2. (a) Foot positioning when wearing a slipper (b) Misfit on lateral side of foot (c) misfit on medial side of foot.

Mismatched flare between the shoes we wear and our . is a primary factor for discomfort in the ball area and in the formation of bunions. Figure 2b and 2c show examples of medial and lateral deformation of the forefoot to fit into a shoe with mismatched flare. The way our feet are "held" will determine how the foot functions and articulates to "sit" inside the shoe. When wearing a slipper (Figure 2a), the strap will dictate the position of the foot. Due to the arch, he foot will move medially to "lock" on to the strap. This results in the foot "sitting" more towards the medial side and hence wear on the inside of the slipper is to be expected. With a shoe, the reverse happens. The feet are not as free to move with a shoe due to the extensive covering on the foot. With shoes, the feet are "clamped" in the heel area due to the stiff material in the heel counter (heel-cup). Hence the shoe or foot can deform only in the forefoot region as a result of the greater flexibility in the forefoot region. Thus, mismatched flare will always result in discomfort in the metatarsophalangeal joint region unless the shoe is much wider than the foot. Mismatched flare results in sizing blems too.

A last is measured by the so-called "stick length" (shoe ize), which is the distance between the two extreme points (corresponding to the posterior point of the heel and the nterior point of the longest toe). Shoe curvature or flare will affect the stick length (Figure 1). A greater curvature gives a shorter stick length (or shoe size), the primary criterion for matching feet to shoes. Foot length is measured s the maximum distance from the heel point to the toes and generally measured along the axis of the Brannock size measurement device. If the shoe curvature does not erfectly fit the foot, the forefoot will have to deform emporarily in the short-term, but permanently if the same lare shoe is worn for a long time) to adapt to the shape of the shoe. This deformation results in a mismatch between he shoe size (or stick length) and the foot length measured long the Brannock axis. Size differences among different manufacturers and different models of shoes are redominantly a result of the last curvature.

What we should know

A study was performed to evaluate the differences between the so-called good fitting shoes and poor fitting shoes. Subjective evaluations pointed to problems as a result of mismatches in the 2-dimensional foot outline and the shoe outline. A mismatched height dimension, generally, creates fewer complaints due to the stretch properties of the uppers and the availability of lacing to adjust the tightness in the "height" dimension. We found that the 2-D outlines can indeed reveal most of the footwear fit problems that people encounter.

By aligning the foot outline and the shoe outline in the heel area, we can quantify the fit mismatch (Figure 3). If the foot is within the boundaries of the shoe, the shoe can be said to be "loose" in the area. Tightness results when the foot outline is outside the shoe boundary. The differences between the shoe outline and the foot outline were quantified using the dimensional difference ("error") as shown in Figure 4. Error was measured as the normal distance from any point on the foot to the shoe outline. We defined tightness as a negative-error and looseness as a positive-error. The variation in error for a good fitting shoe and poorly fitting shoe is shown in Figure 4. The effects of flare are very clear from Figure 4. When the shoe heel region is aligned with the heel, mismatches in the shape between the shoe and the foot requires the shoe or foot to deform. If the shoe does not match the foot, the foot will articulate in the forefoot area in order to "sit" inside the shoe. Mismatched flare will always result in an excess level of error in the metatarsal region as shown in Figure 4. The example shown in Figure 4 can explain why narrow shoes can result in a better fit. When the flare of the shoe matches that of the foot, positive and negative errors are both reduced and hence a narrow shoe with the right flare will fit better than a wider shoe with the incorrect amount of flare. The curves shown in Figure 4 can even be adjusted to account for variations in fit when using socks of different thicknesses. The shape of the "error" curve and the descriptive statistics of the error measure can be used to quantify the quality of the fit.

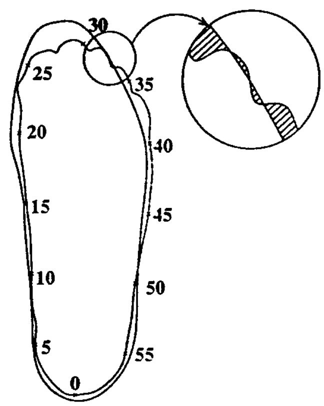


Figure 3. An unconstrained foot and its relative position inside a shoe. The numbers correspond to the length (in cm) along the perimeter.

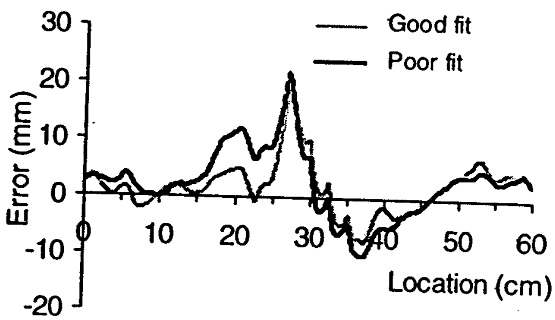


Figure 4. Dimensional difference (Error) between foot and shoe against foot location as marked in Figure 3. Errors are calculated with respect to the unconstrained foot when wearing socks.

What we don't know

Even though the mechanisms causing discomfort are known (Goonetilleke, 1998), the variations in the level of discomfort with varying pressure are still not quantified completely. The availability of this information and the quality of the fit measure proposed in this paper can lead to significant improvements in the prediction of footwear fit.

CONCLUSIONS

Kolarik (1995) stated "The customer will judge his or her shoe fit by wearing the shoes, but at the factory we must use "substitute " characteristic like length, width, and so on, to design, develop and produce our product". The use of the "error" metric can not only improve fit but will allow footwear manufacturers to design lasts that match a given population. Some of our current work also involve determining the minimum number of points to model the shape of feet and the development of parameters to quantify the shape of different feet so that the mapping from feet to shoes is straightforward.

ACKNOWLEDGMENTS

The work described in this paper was fully supported by a grant from the Research Grants Council of the Hong Kong Special Administrative Region, China (Project No. HKUST 798/96E). A special thanks to Dr. Virginia Unkefer for reviewing the manuscript.

References

ANSI/ASTM F539-78 (1986). Standard practice for fitting athletic footwear, 229-235.

British Standard (1980). Methods for measurement and recording for orthopaedic footwear. BS 5943, 1980.

Cavanagh, P. R. (1980). The running shoe book. Mountain View, CA: Anderson World.

Cheskin, M. P. (1987). The Complete Handbook of Athletic Footwear. New York: Fairchild Publications.

Goonetilleke, R. S. (1998). Designing to Minimize Discomfort. Ergonomics in Design, 6(3), pp. 12-19.

Goonetilleke, R. S. and Luximon, A. (in press). Foot flare and Foot axis. Human Factors.

Holscher E. C. and Hu K. K. (1976). Detrimental Results with the common Inflared Shoe. Orthopedic Clinics of North America, 7, 1011-1018.

Karwowski, W. and Jamaldin, B. (1996). Methodological framework for quantifying compatibility of complex ergonomic systems. In Proceedings of the 4th Pan-Pacific Conference on Occupational Ergonomics (pp. 676-679). Taipei, Taiwan: Ergonomics Society of Taiwan.

Kolarik, W. J. (1995). Creating Quality. New York: McGraw-Hill.

Meyer, H. (1860). Why the Shoe Pinches. Quoted from Cavanagh, P. R. (1980). The running shoe book. Mountain View, CA: Anderson World.

Putz-Anderson, V. (1988). Cumulative Trauma Disorders. NY: Taylor and Francis.

Rossi, W. A. (1988). The futile search for the perfect shoe fit. Journal of Testing and Evaluation, 16, 393-403.

Foot Flare and Foot Axis

RAVINDRA S. GOONETILLEKE[1] and AMEERSING LUXIMON, Department of Industrial Engineering and Engineering Management, Hong Kong University of Science and Technology, Clear Water Bay, Kowloon, HONG KONG

Most commercial footwear are designed and manufactured on a curved last even though the amount of "curvature" of the last and the turning point of the last centerline have not been formally determined. This study used principal component analysis to determine the foot axis so that lasts that match the feet could be produced with the end result being good fit. A total of 50 Hong Kong Chinese participants were evaluated. The results show that the foot center is located at approximately 52 % of foot length from the back of the foot (standard deviation = 0.65%) and that Hong Kong participants have a mean inflare (inward curvature) of 3.2 degrees. The "foot center" and the inflare measures are very robust and will help determine the goodness of fit between footwear and feet. Applications of this research include the ability to incorporate foot flare into the design and manufacture of footwear.

[1]Requests for reprints should be sent to Ravindra S. Goonetilleke, Dept. IEEM, HKUST, Clear Water Bay, Kowloon, Hong Kong.

Running title: FOOT FLARE

Key words: foot axis, footwear, flare, last, anthropometry, foot, foot shape, curved last, straight last

INTRODUCTION

Footwear are built using a three-dimensional mold called a shoe *last* (Figure 1). During manufacture, the upper part of the shoe is forcefully pulled around the *last* thereby giving footwear its characteristic shape. Consequently, the last size and shape determine the fit and comfort of a shoe (Cheskin, 1987; Hawes, Sovak, Miyshita, Kang, Yoshihuku, and Tanaka, 1994b; Kouchi, 1995; Rossi, 1988).

Insert Figures 1 and 2 about here

One striking feature of a last is the piecewise linear centerline as shown in the bottom view of Figure 1. This feature can be identified by looking at the shoe outsole or the bottom of a last. Two important characteristics of this centerline are evident: the point at which the turn begins and the amount of the turn. However, researchers have characterized only the amount of turn in a last using an indirect measure that quantifies the longitudinal curvature of the last (Cavangh, 1980; Cheskin, 1987). This measure, called flare, is shown as the angle β in Figure 2. Without knowing the point at which the centerline shifts, it is clear that for any one value of the flare angle, β (Figure 2) of the last, an infinite number of possibilities exist for the angle α in Figure 1. Thus, it is not surprising that footwear manufacturers have downplayed the importance of the flare in the design and manufacture of a last.

On the other hand, foot flare quantifications have not helped the footwear industry. Foot flare has been defined in several different ways, and each definition is based on a somewhat different measurement approach. One of these involves angular measurement (Foot Flare Angle), which is itself specified according to different reference points (Yavatkar, 1993) and somewhat similar to the measurement of the longitudinal curvature on a last; another, Foot Flare

Ratio, utilizes the ratio between key linear distances on the foot (Freedman, Huntington, Davis, Magee, Milstead, and Kirkpatrick, 1946; Randall, Munro, and White, 1951). The foot flare ratio has no equivalent on the last since the matching points on the last corresponding to the anatomical landmarks used in figuring the ratio cannot be determined.

Figure 3 illustrates these two approaches to foot flare measurement (Freedman, et al., 1946; Yavatkar, 1993). Both assume that flare can be represented with respect to the heel centerline (e.g., obtained by joining the two center points of the lines located 10mm and 50mm from point H in Figure 3 or using a similar approach). They differ on how the reference line is defined and how the amount of flare is quantified.

The lack of a proper metric to quantify foot flare in relation to a last (Figure 1) has resulted in mismatches between feet and shoes causing fitting problems and discomfort.

Insert Figures 3 and 4 about here

Impact of flare mismatch

Figure 4 shows examples of flare and its effect on shoe fit. Figure 4a shows a matching foot and shoe and how the foot "sits". In Figure 4b, a clear mismatch between shoe and foot flare/turning point can be seen. If this shoe is worn, the forefoot needs to deviate from its neutral position in order to slide into the shoe, resulting in pressure on the lateral side of the metatarso-phalangeal joint (Figure 4c). Prolonged use of the shoe will result in stretching of the upper material and possible overhang and/or a permanent deformation of the foot. Selecting a wider width shoe can relieve this condition. However, in this case, the clearance on the medial side of the foot may be excessive for a good fit (Figure 4d). The opposite effect will be seen if the foot

has a greater inflare (i.e., turning inward or medially) than the shoe. That is, there will be excess pressure on the medial side and clearance on the lateral side with a wider shoe. Rossi (1988, p 396) cited the mismatch between the foot and the last axes as the "single most serious fault of shoe fit", resulting in most shoes having a run-over at the outer ball area or the upper overlapping the outsole edge, etc. Persons wearing new footwear often suffer from pinching or even chafing of the feet. This is particularly common in the forefoot and heel parts of the feet during the breaking-in process when the shoes adapt to the feet. The recommendation of shoe-fitters is to use a shoe-tree to stretch the upper material. Most shoe-trees are straight and, interestingly, have the effect of reducing or deforming the inflare built into the shoe, and again, suggesting a mismatched flare between the shoe and the foot. Obviously, matching the flare of the foot and shoe is critical to achieving a goof fit and to reducing discomfort.

As shown in Figure 4, a flare mismatch can result in people purchasing footwear that are wider than their feet. If the amount of flare, the turning point and the sizing (length, width and so forth) can all be incorporated into one co-ordinate system, such as the one we are proposing in this paper, many of the redundancies and problems related to footwear may be resolved.

Foot Measurement

Most anthropometric sources report only foot length, width and height dimensions (Pheasant, 1994; Baba, 1975; Rossi, 1983). Are foot length and foot width the right measures to match feet with footwear? Goonetilleke, Ho, and So (1997) showed that there is a correlation ($R^2 = 0.43$) between foot length and foot width in a pool of Hong Kong participants. The reason for using only foot length at times, for fitting purposes, may be attributed to the relationship between foot length and foot width. In other words, the length and width axes, even though orthogonal, are

still correlated. Moreover, as illustrated in Figure 4d, an additional problem is posed when a mismatched flare results in the selection of a wider shoe, thereby making the width measurement redundant.

Such conditions can be avoided by using a set of axes that are orthogonal and uncorrelated as obtained by using principal component analysis (Johnson and Wichern, 1992), thereby measuring different "dimensions" of data. The principal components partition the total variance by first finding the linear combination of the variables (in this case two variables) that account for the maximum variance:

$$P_1 = a_{11}x + a_{12}y \qquad (1)$$

P_1 is called the first principal component. The coefficients of the principal component are the elements of the eigenvector corresponding to the largest eigen value. The coefficients are obtained by solving an eigen value problem. The procedure results in a second linear combination (P_2), uncorrelated with the first component (P_1), such that it accounts for the next largest amount of variance. The second component P_2 is given by:

$$P_2 = a_{21}x + a_{22}y \qquad (2)$$

The principal components are ordered so that the first component displays the largest amount of variation, an important property especially when considering anthropometry.

Study Rationale

Without an established and commonly accepted turning point of the last centerline for any given "population", current footwear design techniques will result in the manufacture of footwear with a multitude of the angle, α (Figure 1), thereby exacerbating the mismatch between feet and footwear.

In this study, we propose a method to quantify foot flare similar to that shown in Figure 1 using principal component analysis (PCA). The objective is to find the "origin" for the flare (or foot center, a point "unknown" to shoe manufacturers), the amount of "flare", and a usable axis system so that these critical foot data can be incorporated into the lasts and the shoes that are subsequently made.

METHODOLOGY

Participants

The participants in this experiment were 50 Hong Kong Chinese males who were staff and students from the Hong Kong University of Science and Technology. The age of the participants was not recorded, but all participants were within the range of 18-39 years. The lower limit of age was based on the fact that the rate of growth of a boy's foot slows down at age 14 and stops at age 17 (Miller, 1989). None of the participants had any foot illness or foot abnormalities.

Procedure

Each participant filled in a voluntary consent form. Their stature and weight were recorded.

The left foot outline was drawn on paper using a scriber (Mochimaru and Kouchi, 1997) when the participants were seated and the foot was in a partially loaded condition. The foot outline was then scanned at 300 pixels per inch and saved in ".tif" graphics format. Using this graphics file, the (X,Y) coordinates of the foot outline were extracted using a program written in Matlab. The software, Surfacer (1995) version 5 was used to process the (X,Y) coordinates further. The foot outline was first oriented such that the Y- axis (*temporary axis* to determine the X and Y coordinates) matched the heel point to mid-point of second toe line (Line HT in Figure 5) using a graphical technique (Kouchi, 1995). Since the thickness of the scribed outline could

vary from point to point, the outline was thinned such that the spatial sampling had a tolerance of 1 mm by using Surfacer. The thinning function reduced a given point cloud to a given tolerance. The points that were retained were guaranteed to be further away from one another than the specified tolerance, while the discarded points were guaranteed to be within the specified tolerance distance from one of the retained points (Surfacer, 1995). Since the outline thickness when drawn using a scriber was around 0.5 mm, using a tolerance of 1 mm in space sampling produced a set of points on the outline spaced at 1 mm distance. After the thinning operation, a smooth, closed B-Spline was fitted (Choi, 1991). B-splines were used since the fitted curve will always pass through all the points in the cloud. The fitted curve was C2 continuous (i.e., second-order curvature continuity) and the number of control points in the curve will always be three more than the number of data points in the selected point cloud. The smoothed closed curve was then uniformly sampled to obtain 1000 points. This procedure ensured that the foot outline was uniformly sampled. The (X,Y) co-ordinates of the 1000 points (Figure 5) were then used for all subsequent analysis using SAS and AUTOCAD.

Insert Figure 5 about here

RESULTS

All statistical analyses were performed using the SAS package. The mean weight, stature, foot length and foot width were 66.2 kg (SD=11.3), 171.98 cm (SD = 6.27), 25.46 cm (SD= 1.23), and 9.32 cm (SD=0.52), respectively (Table 1).

Insert Table 1 about here

Foot length (FL) was defined as the longest length measured along the Brannock device™ axis. For those participants whose second toe was longer than the first (9 out of 50 or 18%), FL was equal to the distance from heel to the tip of the second toe. Similarly, for those with the big toe longer than the second (82% of participants), FL was equal to the distance between the heel and the big toe. Pheasant (1994) reported foot lengths of 235mm, 250mm, and 265 mm for the 5th, 50th and 95th percentiles of Hong Kong Chinese participants. In our study, the minimum, mean and maximum values for foot length were 226.4, 254.6 and 277.9 mm, indicating that the participant pool was representative of the Hong Kong Chinese population (according to popular anthropometric criteria related to the foot).

The mean co-ordinates (X_{mean}, Y_{mean}) of the 1000 points were also calculated. The Y_{mean} was normalized with respect to the foot length as (Y_{mean} /FL). Interestingly, this normalized value was relatively the same (mean = 51.96% with SD= 0.65% and mean = 52.47% with SD=0.67%) for all participants (Tables 2 and 3).

To determine the orthogonal axis system that best describes the human foot, a principal component analysis (PCA) was performed on the coordinates of the 1000 points for each sample using SAS. The angle (θ) between the "arbitrary axis" (HT) defined for measurement and the principal component axis, P_1, was obtained (Figure 5) using the coefficients of equations (1) and (2) as follows:

$$\theta = \tan^{-1}(a_{11} / a_{12}) \quad (3)$$

For example, the PCA for participant 1 resulted in the following:

$$P_1 = 0.028631 * X + 0.999590 * Y \quad (4)$$

$$P_2 = 0.999590 * X - 0.028631 * Y \quad (5)$$

Thus,

$$\theta = \tan^{-1}(0.028631/0.99959) = 1.641^0 \quad (6)$$

All inflare (clockwise) angles were denoted as negative angles. Hence participant 1 has an angle θ equivalent to −1.641 degrees. The results from all participants are given in Tables 2 and 3. To show potential differences, the results of the participants with toe 2 length > toe 1 length and those with toe 1 length > toe 2 length are shown separately.

Insert Tables 2 and 3 about here

Flare has always been defined with respect to the heel centerline (Yavatkar, 1993; Freedman et al., 1946). For comparison purposes, all flare measures were obtained with respect to the heel centerline (axis obtained by joining the centers of the 10 mm and 50 mm lines as shown in Figure 3). The values for flare obtained from the principal component method (α) (Figure 5), Freedman's method (Figure 3), and Yavatkar's method (Figure 3) are shown in Tables 4 and 5. The descriptive statistics of the three methods are given in Table 6.

To compare the three different flare measures, a linear regression analysis was performed. The equations for the relations are as follows:

$$(\text{PCA Flare}) = 1.167 * (\text{Yavatkar flare}) - 2.5 \qquad R^2 = 0.9529 \quad (7)$$

$$(\text{PCA Flare}) = -37.805 * (\text{Freedman flare}) + 16.244 \qquad R^2 = 0.8974 \quad (8)$$

$$(\text{Yavatkar Flare}) = -32.33 * (\text{Freedman flare}) + 16.03 \qquad R^2 = 0.9372 \quad (9)$$

The results of the regression analyses are shown in Figures 6, 7, and 8. The equations show that the linear fit is reasonably good among the three methods of flare computation. This suggests that the PCA gives similar results compared to the other computations of flare and is indeed a good representation of the published measures of flare.

Insert Figures 6, 7, 8, Tables 4, 5, 6, and 7 about here

To diffuse any argument implying that flare is related to foot length and/or foot width, a correlation analysis was also performed (Tables 7). The data from all participants show that the flare has very low correlation ($R^2 < 0.1$) with both foot length and foot width. However, for the group whose second toe was longer than the first toe, all flare measures seem to have a reasonably high correlation ($R^2 > 0.5$) with foot width. The low number of participants (N=9) may be a possible reason for the differences between the two groups.

Interestingly, the correlation analyses appear very different between the two groups (toe 1> toe 2 and toe 2 > toe 1). Due to the aforementioned differences, an analysis of variance (ANOVA) was performed with the two groups as the independent variable and the three flare measures as the dependent variable. The results showed no significant ($p > 0.05$) difference between the two groups.

DISCUSSION

Footwear manufacturers have been unable to transform the proposed measures of foot flare to a suitable measurement on the last. Thus, footwear manufacturers have downplayed the significance of flare even though each brand of shoe is manufactured with different 'levels' and origins of flare giving rise to a different degree of fit, as shown in Figure 4. Even Randall et al. (1951) after having performed extensive computations on the data collected by Freedman et al. (1946), questioned the use of the foot flare measures because "the relation of its (foot) longitudinal axis to that of a last or a shoe is unknown" (p. 12). The method proposed in this paper allows a one-to-one mapping from foot to last.

In order to ensure that the angle resulting from PCA represents flare, we performed a regression analysis among the three methods of foot flare computation. The relatively high regression coefficient ($R^2 > 0.89$) among the three methods of flare computation (Figures 6 and 7) indicates that the principal component method is comparable to the other two measures of flare computation proposed in the literature. It should be clear to the reader that a high correlation between any two methods does not imply that the measures of flare are the same. Instead, it implies that all of them behave similarly.

PCA uses objective measures to obtain a set of uncorrelated axes. Botanists and zoologists have relied on PCA to summarize bodily measurements to determine overall indications of size and shape. This problem, known as "allometry", has received considerable attention and PCA has been found to be extremely reliable and useful for such applications (Hopkins, 1966; Sprent, 1972; Mosiman, 1970; Jolicoeur and Mosimann, 1960). Characterizing foot shape falls into a similar category and hence PCA can be inferred to be a very appropriate method. The methods that have been proposed before for the calculation of foot flare (Foot Flare Ratio and Foot Flare Angle) rely on a few landmarks on the foot (Figure 3) and the underlying principle in these quantifications is not clear. Deformities or injuries in and around the desired locations and difficulties in identifying these landmarks on the foot can have a significant impact on the previously calculated flare measures.

A notable result in this experiment is the mean co-ordinate for y, normalized with respect to the foot length. Table 2 shows that the normalized value varies between 50.58 % and 53.44% with a mean of 51.96% and a standard deviation of 0.65%. A similar result holds for those participants whose second toe is longer than the first toe. This implies that the foot center along the Y-axis is relatively "constant" for any foot length. Or, that the "foot center" is proportional to

the foot length, an important property when designing lasts of various sizes (known as grading in the shoe trade). The principal component axis begins at this mean value. Hence, the deviation of the foot axis (Figure 1) in a last can be based upon the direction of the first principal component, P_1 (Figure 5).

Insert Figure 9 about here

The principal component axes, P_1 and P_2 (Figure 5) can also be used for the measurement of other dimensions of the foot. There is otherwise no axis for the foot to match the last or footwear. The orientation of the principal axis seems to match the last centerline in the forefoot region and center of weight movement during slow gait (Figure 9) too. It also gives an indication of where the last centerline needs to shift to accommodate the forefoot part of the foot. This has been another weakness in earlier research. Even though the amount of overall longitudinal curvature of a foot has been quantified, the exact mapping of the measure to the shoe last was not understood. With the determination of the principal component axis of the foot, the mapping to the last is simple and straightforward.

CONCLUSIONS

Data from a group of Hong Kong Chinese male participants whose foot anthropometry ranged below the 5th percentile to above the 95th percentile (on foot length), have helped to determine that the mean flare of a foot is approximately 3.2 degrees, varying from 8.6 degrees of inflare to 2.6 degrees of outflare. This may not always be true with other ethnic populations, females, children, etc. Further study is warranted to obtain a universal result using the method

proposed in this paper. It should be noted that most footwear are manufactured on a 6- to 12-degree inflare, which is a major cause of poor fit and potential injury.

The foot flare measure we obtained through principal component analysis can be considered to be robust due to the objective analysis and the fact that it correlates very well with the other methods proposed in the literature. The foot flare measures proposed by Freedman et al. (1946) and Yavatkar (1993) are very sensitive to the few anatomical landmarks used in those measures, and do not have a clear correspondence to shoe lasts. The locations of points A, B, C, D, and M (Figure 3) can be very difficult to establish leading to errors in the quantification of flare angle. Also, it is difficult, if not impossible, to locate the corresponding points on the shoe. Hence, the previously quantified foot flare measures have had very little use due to the nonexistence of a one-to-one mapping from foot to last.

This study has provided a methodology for quantifying foot flare and determining the centerline shift point (or origin) on the last (Figure 5). Even though flare has been quantified before, the axis turning point has never been questioned or evaluated. A poor matching between the foot axis and the last axis can result in serious deformation of the shoe made from the last and will put pressure on the sides of the foot (Figure 4). The mismatch between the shoe interior and the foot outline (2-dimensional), more specifically a mismatch between the axes, is the source of many fitting problems. It should be noted that the method described in this paper is in relation to static fit (Rossi, 1983). However, it is hypothesized that dynamic fit studies will allow the material properties of footwear to be quantified in order to accommodate foot deformations during activity.

In summary, this paper has achieved the following:

1. A methodology to quantify flare in a reliable way so that the last axis corresponding to the foot axis can be determined.
2. Determined the amount of flare and the turning point for any given foot using principal component analysis.
3. Determined a set of orthogonal and independent axes to characterize the foot unlike the traditionally used measures of foot length and foot width.

Finally, it is hypothesized that matching the foot axis to the last (and shoe) centerline as proposed here will result in a good "fit", reduced injury and discomfort, and most of all consumer satisfaction.

ACKNOWLEDGMENTS

The work described in this paper was fully supported by a grant from the Research Grants Council of the Hong Kong Special Administrative Region, China (Project No. HKUST 798/96E). A special thanks to Prof. Martin Helander and Dr. Virginia Unkefer for reviewing the manuscript.

REFERENCES

Baba, K. (1975). Foot measurement for shoe construction with reference to the relationship between foot length, foot breadth and ball girth. Journal of Human Ergology, 3, 149-156.

Cavanagh, P. R. (1980). The running shoe book. Mountain View, CA: Anderson World.

Cheskin, M. P. (1987). The Complete Handbook of Athletic Footwear. New York: Fairchild Publications.

Choi, B. K. (1991). Surface Modeling for CAD/CAM. Advances in Industrial Engineering, Vol. 11. Amsterdam: Elsevier.

Freedman, A., Huntington, E. C., Davis, G. C., Magee, R. B., Milstead, V. M., and Kirkpatrick, C. M. (1946). Foot dimensions of soldiers (Third Partial Report Project No. T-13). Armored Medical Research Laboratory, Fort Knox, Kentucky.

Goonetilleke, R. S., Ho, C.-F., and So, R. H. Y. (1997). Foot Anthropometry in Hong Kong. In Proceedings of the ASEAN 97 Conference, (pp. 81-88). Kuala Lumpur, Malaysia.

Hawes, M. R., Sovak, D., Miyashita, M., Kang, S-J., Yoshihuku, Y., and Tanaka, S. (1994b). Ethnic differences in forefoot shape and the determination of shoe comfort. Ergonomics, 37(1), 187-196.

Holscher, E. C. and Hu, K. K. (1976). Detrimental results with the common inflared shoe. Orthopedic Clinics of North America, 7, 1011-1018.

Hopkins, J. W. (1966). Some considerations in multivariate allometry. Biometrics, 22, 747-760.

Johnson, R. A. and Wichern, D. W. (1992). Applied Multivariate Statistical Analysis. Englewood Cliffs, NJ: Prentice Hall.

Jolicoeur, P. and Mosimann, J. (1960). Size and shape variation in the painted turtle: A principal component analysis. Growth, 24, 339-354.

Kouchi, M. (1995). Analysis of foot shape variation based on the medial axis of foot outline. Ergonomics, 38, 1911-1920.

Miller, R. G. (1989). Manual of Shoemaking. Clarks Ltd. Printing Department.

Mochimaru, M. and Kouchi, M. (1997). Automatic calculation of the medial axis of foot outline and its flexion angles. Ergonomics, 40, 450-464.

Morton, D. J. (1935). The human foot. New York: Columbia University Press.

Mosiman, J. E. (1970) Size allometry: size and shape variables with characterizations of the lognormal and generalized gamma distributions. J. Amer. Statist. Assoc., 65, 930-945.

Pheasant, S. (1994). Bodyspace. London: Taylor and Francis.

Randall, F. E., Munro, E. H., and White, R. M. (1951). Anthropometry of the foot (Report No. 172). Environmental Protection Section, Quartermaster Climatic Research Laboratory, Lawrence, Massachusetts.

Rossi, W. A. (1983). The high incidence of mismated feet in the population. Foot and Ankle, 4(2), 105-112.

Rossi, W. A. (1988). The futile search for the perfect shoe fit. Journal of Testing and Evaluation, 16, 393-403.

Sprent, P. (1972). The mathematics of size and shape. Biometrics, 28, 23-37.

Surfacer Version 5.0. (1995). User's Guide, Imageware Inc. An Arbor, Michigan, USA.

Yavatkar, A. S. (1993). Computer Aided System Approach to determine the Shoe-Last Size and Shape based on statistical approximated model of a human foot. Unpublished Masters Thesis. Tufts University, Medford MA.

Table 1. Descriptive statistics of participants (N = 50)

Characteristic	Mean	Std. Dev.	Min	Max
Weight (Kg)	66.2	11.3	50.4	103.3
Height (mm)	1719.8	62.7	1583.0	1849.0
Foot Length (mm)	254.6	12.3	226.4	277.9
Foot Length (Brannock)	8.5	1.5	5.0	11.0
Foot Width (mm)	93.2	5.2	79.7	104.1

Table 2. θ, center of principal axis (X_{mean}, Y_{mean}), Foot Length (FL) and Y_{mean}/FL for participants (N = 41) having Toe 1 longer than Toe 2. A negative angle denotes a clockwise angle from the heel-to-2nd toe tip (HT) axis.

Participant	θ (degrees)	X_{mean}	Y_{mean}	FL	Y_{mean}/ FL
1	-1.641	-2.74	132.55	251.0	0.5281
2	-2.686	0.02	132.29	256.7	0.5154
3	-2.449	0.18	128.65	244.4	0.5264
4	-1.780	-2.00	132.59	261.0	0.5080
5	-0.524	3.32	118.41	228.7	0.5178
6	-2.847	1.20	134.49	260.9	0.5155
7	-1.391	1.55	132.98	253.5	0.5246
8	-2.485	0.41	123.25	239.2	0.5153
9	-1.199	2.41	126.52	246.3	0.5137
10	-0.706	-2.63	127.00	238.7	0.5320
11	-1.286	-1.40	128.45	243.6	0.5273
12	-1.939	-1.25	143.33	273.5	0.5241
13	-0.565	-3.65	123.07	234.0	0.5259
14	-1.062	0.36	137.07	260.2	0.5268
15	-3.942	-1.44	122.99	235.1	0.5232
16	-1.935	0.82	131.89	253.9	0.5195
17	-2.035	-0.85	144.07	269.6	0.5344
18	-1.423	-1.14	135.03	258.9	0.5216
19	-2.540	-1.84	136.59	264.1	0.5172
20	-2.464	-2.30	141.74	274.3	0.5167
21	-2.558	-2.87	134.83	259.4	0.5198
22	-1.861	1.02	127.86	247.2	0.5172
23	-1.893	0.10	134.18	259.9	0.5163
24	-2.199	0.48	132.67	256.2	0.5178
25	-3.101	0.77	137.89	266.9	0.5166
26	-1.985	1.02	137.43	268.8	0.5113
27	-2.440	1.65	133.76	263.8	0.5070
28	-1.746	-4.24	129.45	247.8	0.5224
29	-2.053	1.90	135.97	259.0	0.5250
30	-2.682	-0.30	127.93	244.8	0.5226
31	-1.553	1.57	122.45	233.7	0.5240
32	-0.948	2.26	139.30	270.4	0.5151
33	-2.101	-0.45	135.04	263.4	0.5127
34	-3.000	1.05	141.66	272.8	0.5192
35	-2.106	3.70	126.75	243.6	0.5203
36	-1.240	0.47	136.25	258.9	0.5263
37	-2.451	1.70	139.57	269.9	0.5171
38	-1.989	-1.44	127.30	251.7	0.5058
39	-0.387	1.29	133.41	253.5	0.5263
40	-1.818	6.10	142.34	277.9	0.5122
41	-1.999	2.77	129.32	251.1	0.5150
Mean	-1.927	0.18	132.64	255.3	0.5196
Std. Dev.	0.751	2.11	6.21	12.4	0.0065
Min	-3.942	-4.24	118.41	228.7	0.5058
Max	-0.387	6.10	144.07	277.9	0.5344

Table 3. θ, center of principal axis (X_{mean}, Y_{mean}), Foot Length (FL) and Y_{mean}/FL for participants (N = 9) having Toe 2 longer than Toe 1. A negative angle denotes a clockwise angle from the heel-to-2nd toe tip (HT) axis.

Participant	θ (degrees)	X_{mean}	Y_{mean}	FL	Y_{mean}/ FL
42	-0.607	0.02	130.29	247.5	0.5264
43	-0.569	-5.20	120.73	226.4	0.5332
44	-1.556	0.29	130.78	250.2	0.5227
45	-1.466	-2.18	134.47	255.3	0.5267
46	-1.735	-1.93	138.31	260.5	0.5309
47	-0.791	-1.16	135.59	259.5	0.5225
48	-1.895	0.42	135.78	256.3	0.5298
49	-0.875	-0.93	136.66	263.8	0.5180
50	0.665	-1.24	123.49	241.1	0.5122
Mean	-0.981	-1.32	131.79	251.2	0.5247
Std Dev	0.793	1.72	6.11	11.7	0.0067
Min	-1.895	-5.20	120.73	226.4	0.5122
Max	0.665	0.42	138.31	263.8	0.5332

Table 4. The three measures of flare for participants (N = 41) with Toe 1 longer than Toe 2. A negative angle denotes a clockwise angle from mid-heel (HL) axis (i.e., inflare)

Participant	Yavatkar (1993) Flare angle	Flare measure from Principal Components	Freedman et al. (1946) Flare ratio
1	-0.90	-3.82	0.496
2	-2.66	-5.86	0.570
3	1.00	-2.11	0.465
4	-2.99	-5.98	0.574
5	3.85	2.59	0.361
6	-1.78	-4.99	0.577
7	1.03	-1.05	0.480
8	-1.09	-4.24	0.533
9	-1.03	-3.71	0.539
10	-1.21	-3.41	0.535
11	-2.15	-5.01	0.560
12	0.35	-2.09	0.496
13	-0.76	-3.06	0.506
14	-0.20	-2.56	0.510
15	-4.33	-8.63	0.627
16	-1.85	-4.95	0.545
17	-3.60	-7.17	0.555
18	-1.95	-4.09	0.567
19	-3.41	-6.38	0.616
20	-1.53	-5.11	0.516
21	-4.33	-7.70	0.638
22	0.98	-1.73	0.477
23	-0.31	-2.48	0.534
24	0.45	-2.36	0.487
25	-0.52	-3.43	0.531
26	-1.75	-4.50	0.552
27	1.79	-1.06	0.444
28	-2.26	-5.08	0.537
29	0.13	-2.25	0.523
30	-2.02	-5.46	0.550
31	1.82	0.46	0.444
32	3.45	1.19	0.405
33	0.42	-2.77	0.486
34	-4.80	-8.06	0.658
35	3.37	0.35	0.405
36	2.61	0.58	0.404
37	-0.39	-2.59	0.527
38	-1.26	-4.46	0.522
39	1.58	0.59	0.445
40	3.01	0.45	0.408
41	3.34	1.22	0.405
Mean	-0.49	-3.19	0.512
Std Dev	2.27	2.73	0.068
Min	-4.80	-8.63	0.361
Max	3.85	2.59	0.658

Table 5. The three measures of flare for participants (N = 9) with Toe 2 longer than Toe 1. A negative angle denotes a clockwise angle from mid-heel (HL) axis (i.e., inflare)

Participant	Yavatkar (1993) Flare angle	Flare measure from Principal Components	Freedman et al. (1946) Flare ratio
42	-1.36	-3.58	0.546
43	-3.24	-5.48	0.560
44	0.80	-1.56	0.482
45	-2.20	-4.49	0.565
46	-2.35	-5.13	0.561
47	-0.01	-2.25	0.489
48	-0.94	-3.03	0.512
49	1.06	-0.58	0.445
50	-0.97	-2.12	0.518
Mean	-1.02	-3.14	0.520
Std Dev	1.45	1.67	0.042
Min	-3.24	-5.48	0.445
Max	1.06	-0.58	0.565

Table 6. Simple Statistics for all flare measures (N=50)

Method	Mean	Std. Dev.	Minimum	Maximum
Yavatkar Flare	-0.58	2.14	-4.80	3.85
PCA Flare	-3.18	2.56	-8.63	2.59
Freedman Flare	0.514	0.064	0.361	0.658

Table 7. Correlation coefficients for all participants (N=50). Those in () are for participants whose toe 1 is longer than toe 2 (N=41). Those in { } are for participants whose toe 2 is longer than toe 1 (N=9).

	Yavatkar flare	PCA flare	Freedman flare	Foot Length	Foot Width
Yavatkar Flare	1	0.98***	-0.97***	-0.03	0.05
		(0.98***)	(-0.97***)	(-0.11)	(-0.05)
		{0.97***}	{-0.95***}	{0.53}	{0.81**}
PCA Flare		1	-0.95***	-0.08	-0.01
			(-0.95***)	(-0.13)	(-0.09)
			{-0.94***}	{0.41}	{0.71*}
Freedman Flare			1	0.08	-0.01
				(0.15)	(0.08)
				{-0.44}	{-0.71}
Foot Length				1	0.69***
					(0.66***)
					{0.84**}
Foot Width [a]					1

* Statistically significant at $p < 0.05$

** Statistically significant at $p < 0.01$

***Statistically significant at $p=0.0001$

NOTATION:

Points:

A	Most outward point at fifth toe
B	Point ahead of A at the longest toe
C	Point ahead of D at the longest toe
D	Most outward point at first toe
H	Heel point (pternion)
L	Intersection point of heel centerline and line BC
M	Mid point of BC
MPJ_l	Lateral metatarsal phalangeal joint
MPJ_m	Medial metatarsal phalangeal joint
O	Origin of the principal component axis
P	Intersection point of perpendicular from MPJ_m to heel centerline HL
Q	Intersection point of perpendicular from MPJ_l to heel centerline HL
T	Mid point of the 2nd toe

Lines:

OP_1	First principal component axis
OP_2	Second principal component axis (perpendicular to OP_1)
HL	Heel centerline using the center points of the 10mm and 50 mm lines. Used as the reference axis for flare calculation
HT	Heel point (H) to mid point (T) of 2nd toe

LIST OF FIGURES

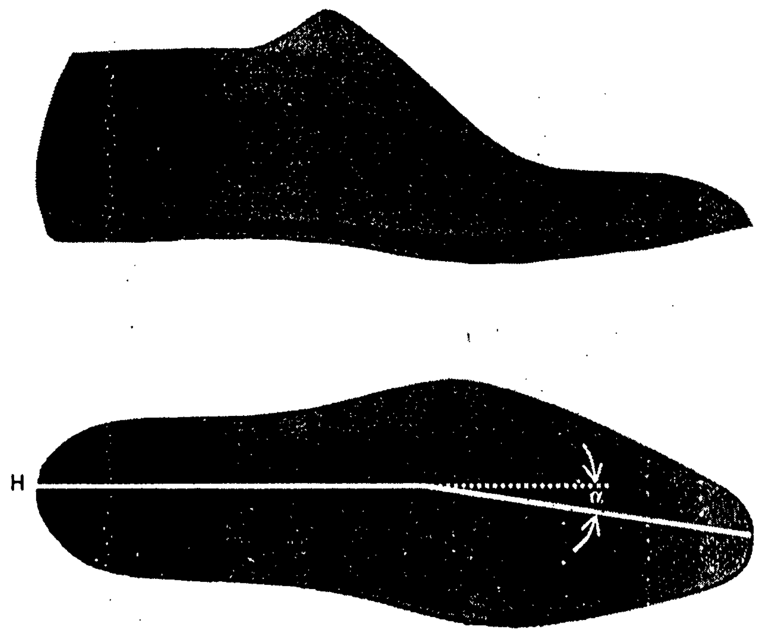


Figure 1. The side view and underside of last. The piece-wise linear centerline is shown in the bottom view.

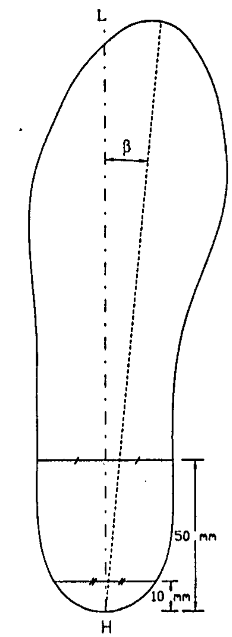


Figure 2. Flare angle (β) on a last. HL is the heel centerline. The other dotted line is the tip-to-tip line commonly referred to as the stick-length axis.

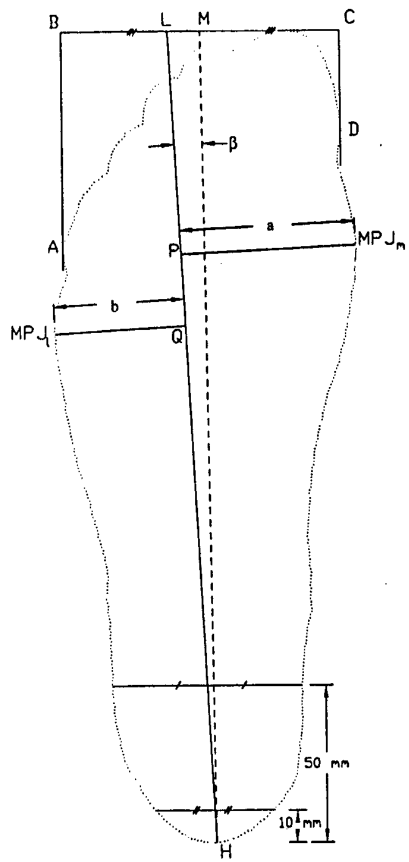


Figure 3. Foot flare ratio{a/(a+b)} as defined by Freedman et al. (1946) and foot flare angle (β) as defined by Yavatkar (1993). B and C correspond to the first and fifth toe projections. Note: BM = MC

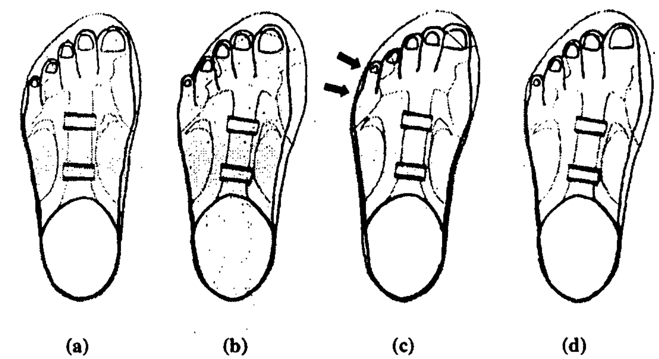


Figure 4. Flare and its effect on shoe fit (a) A matching shoe (b) Mismatch of axis between shoe and foot (c) Deviation in forefoot to fit into shoe resulting in pressure on toes (d) A mismatched foot and shoe with no deviation in forefoot. Fit obtained using a wider shoe thereby resulting in excess clearance on medial side (Adapted, with permission, from *the Journal of Testing and Evaluation*, Volume 16, No. 4, copyright American Society for Testing and Materials, 100 Barr Harbor Drive, West Conshohocken, PA 19428).

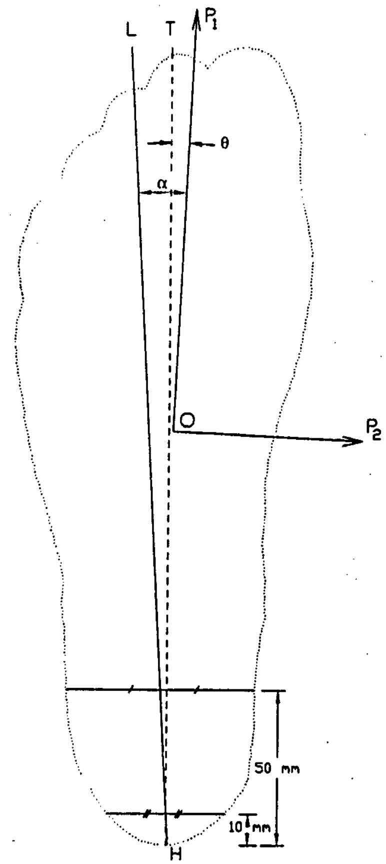


Figure 5. **Principal axis orientation (θ) with respect to heel-2^nd toe (HT) axis and Flare angle (α) of the principal axis**

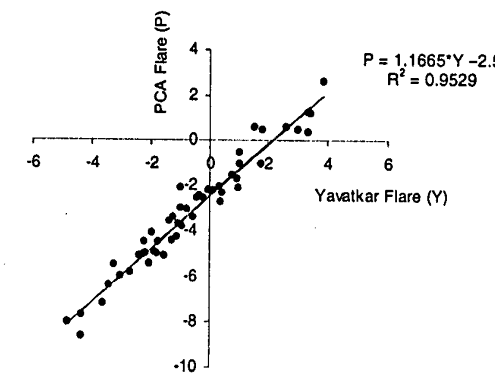


Figure 6. Regression analysis of flare between principal component method (P) and Yavatkar's (Y) method

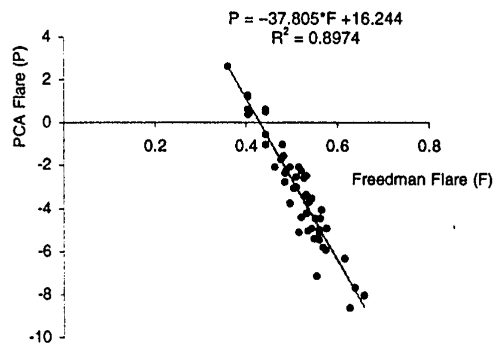


Figure 7. Regression analysis of flare between principal component method (P) and Freedman's (F) method

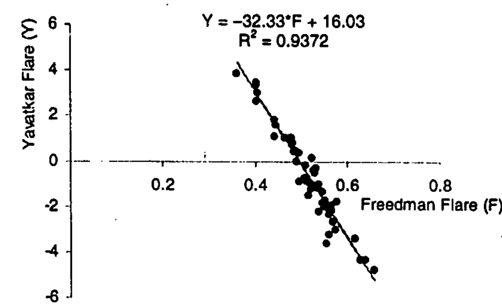


Figure 8. Regression analysis of flare between Freedman's (F) method and Yavatkar's (Y) method

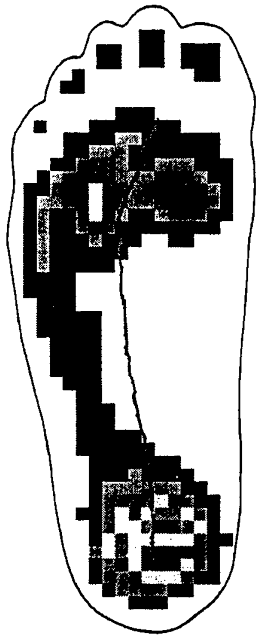


Figure 9. Foot print and center of pressure movement during slow (0.5 mph) barefoot walking on treadmill.

Ravindra S. Goonetilleke and Ameersing Luximon (Foot Flare and Foot Axis)

RAVINDRA S. GOONETILLEKE is an Assistant Professor in the Department of Industrial Engineering and Engineering Management at the Hong Kong University of Science and Technology. He received his B.Sc. (Hons.) degree in Mechanical Engineering from the University of Moratuwa, Sri Lanka. He received a M.S.A.E. degree in Aerospace Engineering from the Georgia Institute of Technology and M.S. (1984) and Ph.D. (1990) degrees in Human Factors Engineering from the State University of New York at Buffalo. He has worked as a Researcher at Nike, Inc. and as a Senior Ergonomist at Biomechanics Corporation of America, New York. His research interests are designing effective product interfaces. Email: ravindra@ust.hk

AMEERSING LUXIMON is a Ph.D. student at the Hong Kong University of Science and Technology, Industrial Engineering and Engineering Management Department (IEEM). He obtained his M.Sc (1996) in IEEM from the Hong Kong University of Science and Technology. He received his B.Tech (Hons) degree in Electrical and Electronic Engineering from the University of Mauritius in 1993. His research interests include anthropometry, consumer product design, mental workload, safety, individual differences and mathematical modeling. Email: ieshyam@ust.hk

FOOT ANTHROPOMETRY IN HONG KONG

RAVINDRA S. GOONETILLEKE, Department of Industrial Engineering & Engineering Management, Hong Kong University of Science and Technology, Clear Water Bay, Kowloon, Hong Kong, Email: ravindra@usthk.ust.hk,
EDMOND CHEUK FAN HO, Department of Industrial Engineering & Engineering Management, Hong Kong University of Science and Technology, Clear Water Bay, Kowloon, Hong Kong, Email: iehcf@usthk.ust.hk
and
RICHARD H. Y. SO, Department of Industrial Engineering & Engineering Management, Hong Kong University of Science and Technology, Clear Water Bay, Kowloon, Hong Kong, Email: rhyso@usthk.ust.hk.

Abstract
Even though numerous devices are available for measuring the foot, generally, only one or two dimensions are used when sizing a foot. The study reported here is an attempt to find "orthogonal" dimensions so that a Hong Kong Chinese foot may be properly sized and modelled. Foot dimensions of thirty one subjects were measured using an anthropometer, digital caliper and a measuring tape. Factor analyses and principal component analysis indicated that the height dimension is important. Hence, it is recommended that at least two dimensions be measured in the forefoot, midfoot and rearfoot to model the foot better.
Index words: Foot, Anthropometry, Sizing.

1. Introduction

Devices such as the Ritz, Brannock, and Scholl are available to measure foot size (Cheskin, 1987). The more popular among the three is the Brannock device, which allows one to measure the following dimensions:

1. Overall length from the tip of the most prominent toe to the heel with three Brannock units corresponding to one inch.
2. Ball joint or metatarsophalangeal joint (MPJ) position with respect to the heel (called arch length) and
3. Width of foot measured at the MPJ joint (or ball of foot) with alphabetic letters of AAA (narrow), AA, A, B, C, D, E, EE, and EEE (wide). The width is normally obtained relative to foot length.

However, in reality, the Brannock device is used for the measurement of only foot length and sometimes foot width. From a mathematical viewpoint, it is almost impossible to generate a foot form of 3-dimensions using a set of 2-dimensional measures of foot length and width. Footwear manufacturers use at least 30 dimensions to build a foot last (Rossi, 1988). Hence the mapping of 2 dimensions to 30 dimensions on a shoe last is clearly inadequate. This paper is an attempt to evaluate the relevant dimensions of the Hong Kong male foot so that they can be categorized or classified better.

2. Methodology

Subjects
A total of 31 Hong Kong Chinese adult male students at the Hong Kong University of Science and Technology were subjects in the experiment. None of the subjects had any foot illness or foot abnormalities.

Procedure

Each subject was asked to fill a voluntary consent form. Their age, stature and weight were first recorded. All measurements were made under "no-load" conditions using an adjustable chair and a height adjustable foot rest with a 90 degree angle at the ankle joint (Figure 1). Fourteen dimensions on the left foot were measured for each subject (Figure 2 and 3).

A *Brannock*[1] Device was used to measure the foot length (D1), foot width (D2), and arch length (D3) defined as the ball-to-heel length in Brannock units. Foot width was not measured as specified in the Brannock device. Instead, the markings which correspond to foot length were used against a reference mark to obtain a numerical value for foot width rather than alphabetic characters between AAA and EEE. This procedure for foot width allows the measurement to be independent of foot length. Independence from foot length is especially important due to the nature of our study. An *anthropometer* was used to measure the foot height or dorsal arch height[2] (D4) and height of MPJ joint at the 1st toe (D5). A *measuring tape* was used to measure the circumference of the MPJ joint (D6). A *digital caliper* was used to measure the length of the 5 toes (T1, T2a, T2b, T3a, T3b, T4a, T4b and T5) as shown in Figure 3.

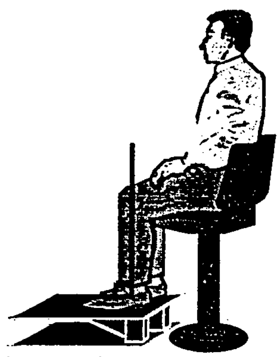


Figure 1. "Unloaded" foot posture during measurement

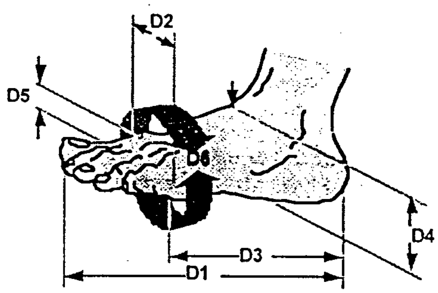


Figure 2. Dimensions D1 to D6

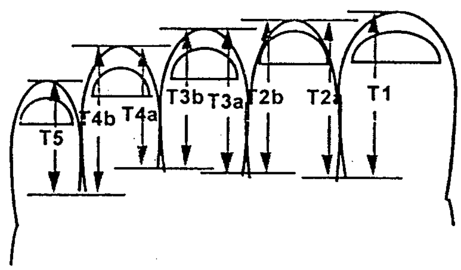


Figure 3. Toe dimensions

[1] *Brannock* is sold by the Brannock Device Company, Syracuse, New York.

[2] Dorsal arch height is the distance from the floor to the point where the top of the foot meets the front of the leg as defined by Pheasant (1994).

3. Transformation

Since D1, D2 and D3 were measured in Brannock units, these three dimensions were converted to length measures using the following transformations:

Foot Length (FL) in mm = $187 + (25.4 / 3) \times (D1 - 0.5)$

Foot Width (FW) in mm = $64.3 + 3.2 \times (D2 - 1)$

Arch Length (AL) in mm = $173.5 + 5.6 \times (D3 - 7)$

where D1, D2 and D3 are in Brannock units.

Most subsequent statistical analyses were performed using the transformed measures of FL, FW, and AL.

4. Results and Analysis

The descriptive statistics of the subjects are shown in Table 1.

Table 1. Descriptive statistics of the subjects (N=31)

Variable	Mean	Standard Deviation	Minimum	Maximum
Age (years)	22.1	1.37	20	25
[3]Stature (mm)	1726	70.67	1550	1870
[3]Weight (kg)	65.62	12.17	43.2	101
Foot Length, D1 (Brannock units)	8.2	1.28	5	10.5
[3]Foot Length, FL (mm)	252.00	10.82	225.1	271.67
[3]Foot Width, FW (mm)	94.03	4.31	85.1	103.98
Arch Length, D3 (Brannock units)	8.8	1.54	5.25	11.6
Arch Length, AL (mm)	183.38	8.60	163.7	199.26
Foot Height, D4 (mm)	75.83	4.31	66.8	84.8
Height of MPJ joint at first toe, D5 (mm)	36.61	1.98	32.8	39.8
Circumference of foot along MPJ joint, D6 (mm)	245.90	12.59	214	275
First toe length, T1 (mm)	43.81	3.13	37.13	50.79
Second toe length on side of first toe, T2a (mm)	41.51	3.98	33.48	50
Second toe length on side of third toe T2b (mm)	37.71	4.04	30.28	45.08
Third toe length on side of second toe T3a (mm)	30.40	3.60	23.09	40.08
Third toe length on side of fourth toe T3b (mm)	36.78	3.86	31.23	44.98
Fourth toe length on side of third toe, T4a (mm)	26.41	3.69	19	35.32
Fourth toe length on side of fifth toe, T4b (mm)	38.94	4.09	31.21	46.62
Fifth toe length on side of fourth toe T5 (mm)	24.93	4.19	15.82	33.48
Toe 1 to heel, T1H (mm)	251.48	10.56	225.1	269.10
Toe 2 to heel, T2H (mm)	249.18	11.13	220.27	271.67
Toe 3 to heel, T3H (mm)	241.87	10.86	219.27	264.55
Toe 4 to heel, T4H (mm)	231.49	10.79	209.70	253.47
Toe 5 to heel, T5H (mm)	217.49	10.99	197.68	241.51

[3] The mean (and standard deviation) for stature, weight, foot length, foot width reported by Pheasant is 1680 cm (58), 59.9 kg (8.6), 250 mm (10), 95 mm (5).

The heel-to-toe length for each of the five toes were calculated as follows:
If T1 > T2a, then T1H = FL and T2H = FL – (T1 – T2a);
If T1 < T2a, then T2H = FL and T1H = FL – (T2a – T1).
Thereafter, T3H = T2H – (T2b – T3a), T4H = T3H – (T3b – T4a), and T5H = T4H – (T4b – T5)

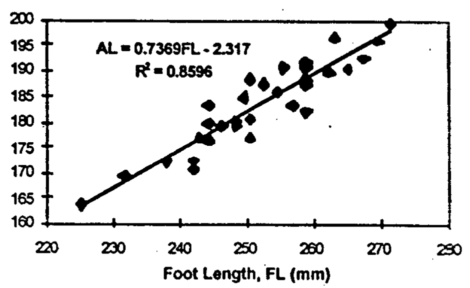
It was seen that 21 out of the 31 subjects (68%) had the big toe (toe 1) longer than the second toe (i.e., T1H > T2H).

The statistical package, SAS was used to perform all analyses. The inter-correlation analysis of all data collected (i.e., FL, FW, AL, D4, D5. D6, T1, T2a, T2b, T3a, T3b, T4a, T4b and T5) shows a significant ($p < 0.05$) correlation between many variables. Pearson correlation coefficients greater than 0.65 ($p < 0.05$) are shown in Table 2.

Table 2. Correlation analysis. Pearson correlation (R) coefficients greater than 0.65 are shown.

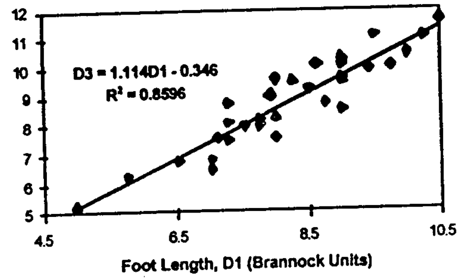
Variables	R^2	Variables	R^2
Foot Length and Stature		T1H and FL	0.99
FL and H	0.44	T1H and FW	0.44
Weight and Foot Width		T1H and AL	0.89
W and FW	0.49	T1H and D6	0.49
Foot width and Foot Length		T1H and T2H	0.89
FW and FL	0.43	T1H and T3H	0.85
Arch length and Foot Length		T1H and T4H	0.81
AL and FL	0.86	T1H and T5H	0.68
Circumference and Weight		T2H and FL	0.93
D6 and W	0.43	T2H and AL	0.81
Circumference and Foot Length		T2H and D6	0.45
D6 and FL	0.49	T2H and T3H	0.95
Circumference and Foot Width		T2H and T4H	0.87
D6 and FW	0.86	T2H and T5H	0.79
		T3H and FL	0.88
T2a and T2b	0.69	T3H and AL	0.78
T2a and T3a	0.57	T3H and D6	0.47
T2a and T3b	0.54	T3H and T4H	0.94
T2b and T3a	0.62	T3H and T5H	0.83
T2b and T3b	0.71	T4H and FL	0.84
T2b and T4a	0.51	T4H and FW	0.45
T3a and T3b	0.69	T4H and AL	0.77
T3a and T4a	0.56	T4H and D6	0.46
T3b and T4a	0.54	T4H and T5H	0.87
T4a and T4b	0.52	T5H and FL	0.73
T4a and T5	0.5	T5H and AL	0.61

A linear regression analysis was performed to obtain the relationship between arch and foot length as well as the linear relationship between foot circumference and foot width. The scatter plots and the fitted lines are shown in Figure 4.

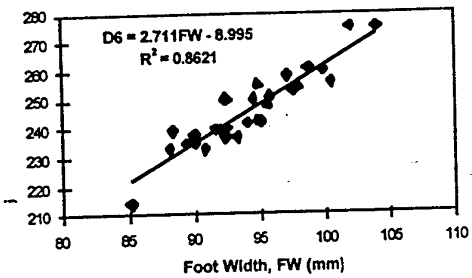


A least squares fit between arch length (AL) and foot length (FL) gave the following results;
AL = (0.7369) FL – 2.317 ;
($p < 0.0001$)

Note that AL and FL are measured in mm.



If Brannock units are used instead, the least squares fit is as follows:
D3 = (1.114) D1 – 0.346 ;
($p < 0.0001$)



Similarly, the least squares fit between foot circumference (D6) and foot width (FW) gave the following results;
D6 = (2.711) FW – 8.995;
($p < 0.0001$)
Note that D6 and FW are measured in mm.

Figure 4. Least squares fit for foot length, arch length, foot width and circumference

Three separate factor analyses (Tables 4, 5, and 6) were performed using the principal component method with varimax rotation. The first was using the toe dimensions (Table 4), the second using the heel to toe dimensions (Table 5) and the third excluding all toe dimensions (Table 6). The first factor analysis (Table 4) showed the emergence of 8 dominant factors (variance explained = 95%). The interesting finding is the grouping of the measured dimensions in the rotated factor loadings as shown in Table 4. Factor 1 is dominated by the toe dimensions of the second, third, and fourth toes ("centre toe lengths"). Foot width (FW) and circumference (D6) dominate factor 2 ("width"), foot length (FL) and arch length (AL) dominate factor 3 ("critical length"). T1 ("big toe length"), D4 ("midfoot height"), D5 ("forefoot height"), T4b, and T5 ("small toe length") dominate separate factors.

The second factor analysis of the variables, FL, FW, AL, D4, D5, D6, T1H, T2H, T3H, T4H, and T5H shows the emergence of 4 dominant factors explaining 95% of the variance. The groupings are such that factor 1 ("length") is dominated by the length measures of FL, AL, T1H, T2H, T3H, T4H, and T5H, factor 2 ("width") by the width related measures of FW and D6, factor 3 by "height" in forefoot area, factor 4 by "height" in the midfoot region. Interestingly, the third factor analysis (Table 6) grouping is the "same" as Table 5 when all toe dimensions are excluded.

Table 4. Factor analysis with varimax rotation including toe dimensions
(Only factor loadings greater than 0.5 are shown)

	Factor													
	1	2	3	4	5	6	7	8	9	10	11	12	13	14
FL	-	-	0.78	-	-	-	-	-	-	-	-	-	-	-
FW	-	0.92	-	-	-	-	-	-	-	-	-	-	-	-
AL	-	-	0.88	-	-	-	-	-	-	-	-	-	-	-
D4	-	-	-	-	0.97	-	-	-	-	-	-	-	-	-
D5	-	-	-	-	-	0.92	-	-	-	-	-	-	-	-
D6	-	0.93	-	-	-	-	-	-	-	-	-	-	-	-
T1	-	-	-	0.92	-	-	-	-	-	-	-	-	-	-
T2A	0.77	-	-	-	-	-	-	-	-	-	-	-	-	-
T2B	0.89	-	-	-	-	-	-	-	-	-	-	-	-	-
T3A	0.88	-	-	-	-	-	-	-	-	-	-	-	-	-
T3B	0.94	-	-	-	-	-	-	-	-	-	-	-	-	-
T4A	0.68	-	-	-	-	-	-	-	-	-	-	-	-	-
T4B	-	-	-	-	-	-	0.84	-	-	-	-	-	-	-
T5	-	-	-	-	-	-	-	0.84	-	-	-	-	-	-
Variance explained by each factor	4.017	2.182	1.723	1.151	1.084	1.066	1.060	0.980	0.235	0.170	0.169	0.096	0.036	0.031
Proportion explained by each factor	28.69%	15.59%	12.31%	8.22%	7.75%	7.62%	7.57%	7.00%	1.68%	1.21%	1.21%	0.69%	0.26%	0.22%
Cumulative Proportion	28.69%	44.28%	56.59%	64.81%	72.56%	80.18%	87.75%	94.74%	96.42%	97.63%	98.84%	99.53%	99.78%	100%

Table 5. Factor analysis with varimax rotation including toe-to-heel dimensions
(Only factor loadings greater than 0.5 are shown)

	Factor										
	1	2	3	4	5	6	7	8	9	10	11
FL	0.92	-	-	-	-	-	-	-	-	-	-
FW	-	0.88	-	-	-	-	-	-	-	-	-
AL	0.91	-	-	-	-	-	-	-	-	-	-
D4	-	-	-	0.98	-	-	-	-	-	-	-
D5	-	-	0.96	-	-	-	-	-	-	-	-
D6	-	0.87	-	-	-	-	-	-	-	-	-
T1H	0.92	-	-	-	-	-	-	-	-	-	-
T2H	0.94	-	-	-	-	-	-	-	-	-	-
T3H	0.92	-	-	-	-	-	-	-	-	-	-
T4H	0.87	-	-	-	-	-	-	-	-	-	-
T5H	0.81	-	-	-	-	-	-	-	-	-	-
Variance explained by each factor	6.028	2.167	1.142	1.100	0.233	0.113	0.078	0.058	0.045	0.034	0.002
Proportion explained by each factor	54.8%	19.7%	10.38%	10.0%	2.12%	1.03%	0.71%	0.53%	0.4%	0.31%	0.02%
Cumulative Proportion	54.8%	74.5%	84.88%	94.88%	97%	98.03%	98.74%	99.27%	99.68%	99.98%	100%

Table 6. Factor analysis with varimax rotation excluding all toe dimensions (Only factor loadings greater than 0.5 are shown)

	Factor 1	Factor 2	Factor 3	Factor 4	Factor 5	Factor 6
FL	0.89	-	-	-	-	-
FW	-	0.89	-	-	-	-
AL	0.94	-	-	-	-	-
D4	-	-	-	0.98	-	-
D5	-	-	0.97	-	-	-
D6	-	0.90	-	-	-	-
Variance explained by each factor	1.928	1.883	1.035	1.028	0.067	0.060
Proportion explained by each factor	32.12%	31.38%	17.25%	17.13%	1.12%	1%
Cumulative Proportion	32.12%	63.51%	80.76%	97.88%	99%	100%

In reality, the toes are not measured. The longest toe is taken to be an important measure resembling the overall length of the foot. Hence, it is reasonable to ignore the toe lengths and consider only foot length. Based on this reasoning, a principal component analysis was performed using the correlation matrix with variables FL, FW, D4 and D5. Foot length (FL) and foot width (FW) were used instead of arch length (AL) and MPJ circumference (D6) since the former two dimensions are commonly used in foot sizing. The results are shown in Table 7. When the natural logarithms were used, the Eigen values and the Eigen vectors hardly changed as shown by the values in parenthesis (see Table 7). It is easier to explain the principal components with the logarithmic transformations as shown below:

For example, Principal component $_1$ $= 0.55*\ln(FL) + 0.58*\ln(FW) + 0.38*\ln(D4) + 0.46*\ln(D5)$

$$= \ln\{FL^{0.55} * FW^{0.58} * (D4^{0.38} * D5^{0.46})\}$$

Hence the first principal component may be viewed as the ln(volume) of foot with adjusted dimensions. For instance, the adjusted length is (length $^{0.55}$), adjusted width is (width $^{0.58}$), and adjusted depth is ($D4^{0.38} * D5^{0.46}$), which accounts in some sense, for the rounded shape of the foot. Similarly, principal component 4 appears to resemble an effect similar to "Poisson's ratio" in the length and width dimensions while principal component 2 may be viewed as a Poisson's ratio in the height and length directions. Principal component 3 on the other hand may be considered as a "minimum height" measure of the foot/shoe.

Table 7. Principal Component Analysis with FL, FW, D4 and D5 (values in parenthesis are for those with the natural logarithmic transformations of each variable).

Eigen values of the Correlation Matrix

	Eigen value	Proportion	Cumulative
PRIN 1	2.12 (2.14)	0.53 (0.53)	0.53 (0.53)
PRIN 2	0.86 (0.86)	0.22 (0.22)	0.75 (0.75)
PRIN 3	0.69 (0.68)	0.17 (0.17)	0.92 (0.92)
PRIN 4	0.33 (0.32)	0.08 (0.08)	1.00 (1.00)

Eigen vectors

	PRIN 1	PRIN 2	PRIN 3	PRIN 4
FL	0.56 (0.55)	−0.44 (−0.46)	−0.17 (−0.17)	0.68 (0.67)
FW	0.58 (0.58)	−0.26 (−0.26)	−0.29 (−0.26)	−0.72 (−0.72)
D4	0.37 (0.38)	0.84 (0.82)	−0.37 (−0.40)	0.15 (0.15)
D5	0.46 (0.46)	0.18 (0.21)	0.87 (0.86)	−0.04 (−0.01)

5. Conclusions and Limitations

The factor analyses suggest that length, width (or circumference), "height" at midfoot and forefoot, and toe dimensions (toe 1, toes 2-4, and toe 5) need to be considered for proper footwear fitting and when modelling the foot. Most often, feet are sized using only length and sometimes length and width. This study shows that proper fit may only be achieved by including not only length and width, but also the third dimension relating to height. Hence it seems reasonable to divide the foot into three regions: forefoot, midfoot and rearfoot. Based on our study, it appears that at least two dimensions in each of the regions may be needed to describe the foot adequately for better fitting.

The principal component analysis indicates, that a "volume" measure, a basic height measure, and two measures indicating dimensional changes in orthogonal directions (similar to a Poisson effect) can explain the variations in the foot. Hence it may be possible to generate an "ideal" (or theoretical) foot which may be "scaled" using principal components to achieve any desired foot shape.

A few limitations do exist in this study. Firstly, even though the foot is a complex structure only fourteen dimensions were measured and analyzed. Secondly, the Brannock device was used to measure foot length, arch length and width. The markings are in units of 0.5 Brannock units and are not as accurate as desired even though the measurement process was very convenient. Hence the measures obtained before transformation may not be as accurate as a caliper or ruler reading.

6. References

Cheskin, M. P. (1987). *The Complete Handbook of Athletic Footwear.* New York: Fairchild Publications.

Pheasant, S. (1994). *Bodyspace.* London: Taylor and Francis.

Rossi, W. A. (1988). The Futile Search for the Perfect Shoe Fit. *Journal of Testing and Evaluation.* Vol. 16(4), pp. 393-403.

CHAPTER 17

Men's classical and fashion wear grading

SIZE CHARTS

Men's size charts are mostly made up of garment rather than body measurements but classified by a **main body measurement** such as the chest for a jacket or the waist and inside leg for trousers. This is because classical men's clothing has little variation in cut and fit and therefore wholesale tailoring size charts have tended to concentrate on garment measurements which are easier to establish. This makes garment measurement quality control easier to achieve. The fit of a man's tailored suit is more critical than, for example, that of a dress, due to the difference in cost and the emphasis on the classical appearance of a suit as opposed to the many style variations and garment types found in women's clothing. Traditional men's clothing is therefore offered in more size categories than women's. Major girth measurements are related to three height categories; short, regular and long. The three height categories, when combined with seven chest girths for a jacket or waist girths for trousers, provide a comprehensive size range to fit a large section of the male population. The extra short or extra long man must go to specialist shops to buy his clothes.

HEIGHT CLASSIFICATION

Height range

Short	160–173
Regular	174–180
Long	181–184

These classifications will mainly affect the vertical garment measurements such as jacket and sleeve length, body rise and outside leg measurements.

CHEST CLASSIFICATION FOR MAN OF REGULAR STATURE

Regular stature is defined by the ratio between the chest and waist. Regular or medium stature reveals a body measurement difference of 12.0 cm in the slimmer male which decreases as the male puts on weight. In other words the waist gets larger in relation to the chest to form the portly or semi-stout figure.

Table 22 Close body measurements for men of medium stature (cm)

Chest girth	86.0	91.0	96.0	101.0	106.0	111.0	116.0
Waist girth	74.0	80.0	86.0	92.0	98.0	104.0	110.0
Difference	12.0	11.0	10.0	9.0	8.0	7.0	6.0

This decreasing difference means that when grading a man's jacket the waist girth is increased more than the seat and the chest.

The following body measurement size chart is for men of regular height and medium stature (as compiled by Philip Kunick FCFI and used with his permission). It is a source chart for a wide variety of classical and fashion clothing. (See Table 23.)

Table 23 Close body measurements for men of medium stature and regular height (cm)

Horizontal measurements									Size increment
1	Chest	86.0 (34")	91.0 (36")	96.0 (38")	101.0 (40")	106.0 (42")	111.0 (44")	116.0 (46")	5.0 (2")
2	Waist	74.0	80.0	86.0	92.0	98.0	104.0	110.0	6.0
3	Seat	91.0	96.0	101.0	106.0	111.0	116.0	121.0	5.0
4	Across back	37.6	38.8	40.0	41.2	42.4	43.6	44.8	1.2
5	Across chest	36.4	38.2	40.0	41.8	43.6	45.4	47.2	1.8
6	Scye width	12.0	13.0	14.0	15.0	16.0	17.0	18.0	1.0
7	Armscye	41.0	43.0	45.0	47.0	49.0	51.0	53.0	2.0
8	Neck base	38.8 (15")	40.0 (15½")	41.2 (16")	42.4 (16½")	43.6 (17")	44.8 (17½")	46.0 (18")	1.2 (½")
9	Shoulder	12.7	13.0	13.3	13.6	13.9	14.2	14.5	0.3
10	Upper arm	26.0	28.0	30.0	32.0	34.0	36.0	38.0	2.0
11	Wrist	16.6	17.2	17.8	18.4	19.0	19.6	20.2	0.6
12	Maximum thigh	49.6	52.8	56.0	59.2	62.4	65.6	68.8	3.2
13	Knee	35.4	36.7	38.0	39.3	40.6	41.9	43.2	1.3
14	Small girth	31.0	32.5	34.0	35.5	37.0	38.5	40.0	1.5
15	Calf	33.4	35.0	36.6	38.2	39.8	41.4	43.0	1.6
16	Minimum ankle	21.0	22.0	23.0	24.0	25.0	26.0	27.0	1.0
Vertical measurements									
17	Stature	174.0	175.0	176.0	177.0	178.0	179.0	180.0	1.0
18	Cervical height	149.4	150.2	151.0	151.8	152.6	153.4	154.2	0.8
19	Depth of scye	19.8	20.4	21.0	21.6	22.2	22.8	23.4	0.6
20	Nape to waist	41.8	42.4	43.0	43.6	44.2	44.8	45.4	0.6
21	Waist to hip	20.8	20.9	21.0	21.1	21.2	21.3	21.4	0.1
22	Hip height	89.2	89.6	90.0	90.4	90.8	91.2	91.6	0.4
23	Knee height	47.8	47.9	48.0	48.1	48.2	48.3	48.4	0.1
24	Outside leg	110.0	110.5	111.0	111.5	112.0	112.5	113.0	0.5
25	Inside leg	81.0	81.0	81.0	81.0	81.0	81.0	81.0	0.0
26	Body rise	29.0	29.5	30.0	30.5	31.0	31.5	32.0	0.5
27	Arm length	62.4	62.7	63.0	63.3	63.6	63.9	64.2	0.3
28	Crotch length	68.6	70.8	73.0	75.2	77.4	79.6	82.0	2.2

For men aged 18 to 30 reduce waist girth by 3.0 cm.

CHAPTER 18

Trouser grading

Sizing men's trousers is usually based on the following three factors:

1 The waist girth measurement
2 The inside leg measurement
3 The trouser bottom width.

The waist girth and the inside leg are body measurements. The trouser bottom width is an important style factor, subject to fashion change.

Six waist sizes are often offered with three length choices, i.e. short, regular and long. The inside leg measurement is normally identified on the ticket with the waist measurement.

A typical trouser size chart will offer a 5.0 cm waist grade and a 5.0 cm inside leg grade and look as follows:

Waist	75.0	80.0	85.0	90.0	95.0	100.0
Inside leg, regular	81.0	81.0	81.0	81.0	81.0	81.0
Inside leg, short	76.0	76.0	76.0	76.0	76.0	76.0
Inside leg, long	86.0	86.0	86.0	86.0	86.0	86.0
Trouser bottom width	Fashion variable					

Note that with more expensive trousers, the current trend is to cut the trouser length generously and turn up the hem at the point of sale.

Figure 238 shows a split diagram with girth and

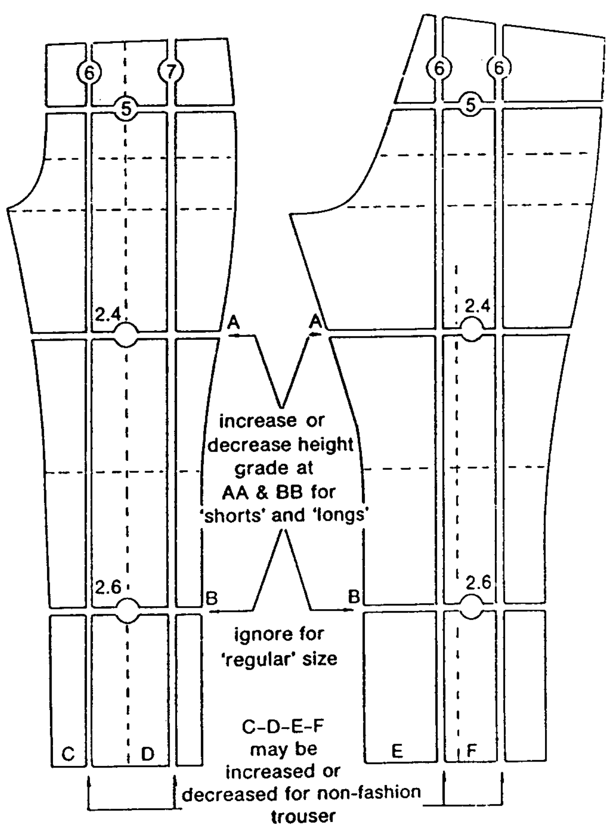


Figure 238
Trouser split diagram

height combined, i.e. 5.0 cm height and 5.0 cm girth. When grading 'Shorts' and 'Longs' the grade is positioned above and below the knee. Also note that the body rise is graded 0.5 cm per size.

Figure 239 shows a grade and grade directions for one size only, using a zero located on the junction of the seat and crease line. In this grade the trouser bottom width remains a constant measurement throughout the size range. As a style option the trouser bottom width can be increased by 0.5 cm every other size to retain the leg shape.

Figure 240 shows the completed five size grade with three leg lengths.

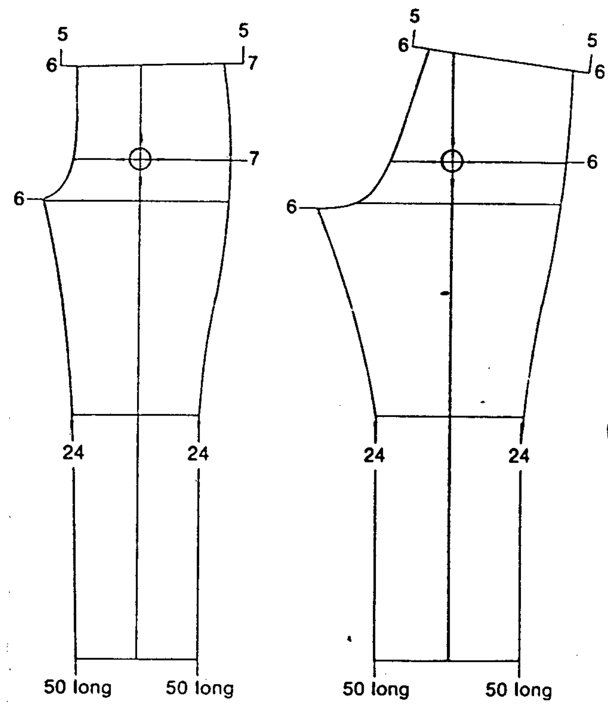


Figure 239 Grade plan for fashion trouser. Static trouser bottom width

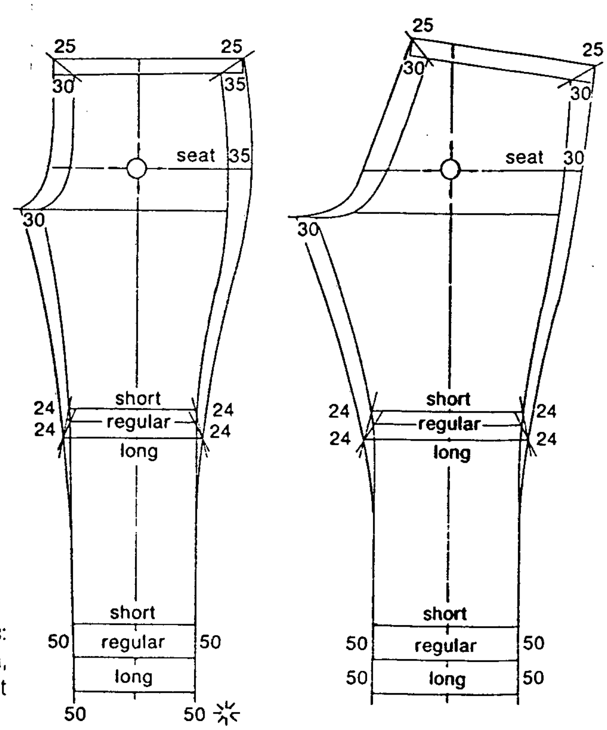


Figure 240 Completed grade for five waist sizes: 80 cm, 85 cm, 90 cm, 95 cm and 100 cm, and two leg lengths 5.0 cm grade. Set bottom width

CHAPTER 20

Shirt sizing and grading

Men's shirts are classified by two main measurements:

1. The neck, which is a **body measurement** and
2. The chest, which is a **loose garment measurement** and will vary according to style.

The shirt style obviously has an effect on the manner in which the shirt is graded. For example, a classically fitting dress shirt or a close fitting shirt for the younger man will need a much more sophisticated grade than a sports shirt which has not been cut to button up at the neck and may be classified simply as Small, Medium or Large.

MAN'S SHIRT (Figure 255)

The usual neck increase is 1.2 cm per size and the customer is offered a size range from 35.6 cm (14") to 46.2 cm (18") – a range of eight sizes. The chest is based on a half size grade of 2.5 cm per size. All other body measurements are halved to establish a consistent grade. An alternative to the half size grade is to grade up the shirt by a full 0.5 cm every other size, i.e. retaining one chest size per two neck sizes.

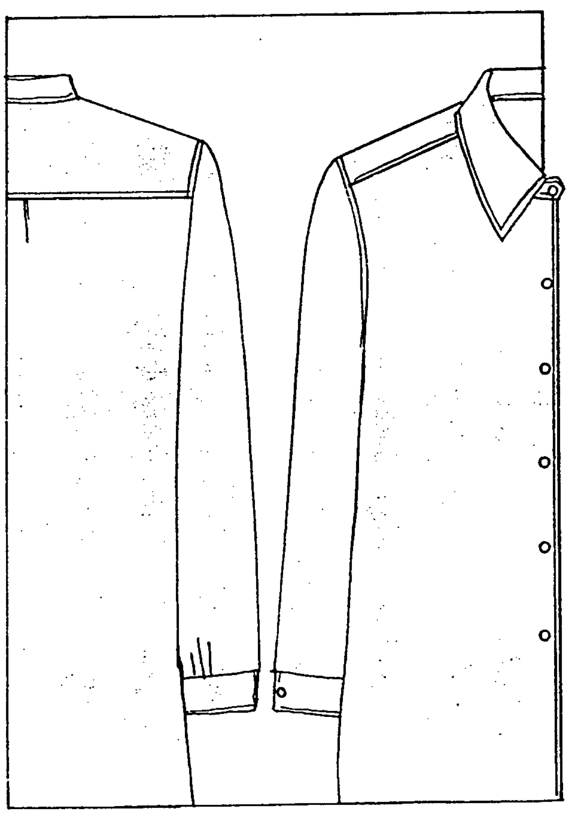


Figure 255 Man's shirt

SIZE CHART (Table 25)

This size chart covers a range of fourteen neck sizes and is based on a 1.2 cm neck grade and a 2.5 cm chest grade. Comparisons with the main men's size chart (Table 25) will be difficult due to the inclusion of the half sizes.

Figure 256 shows the one size grade plan. It is important to note that increments are rounded to the nearest whole millimetre. The one piece and the two piece collar grades are shown.

The grade angles are based on the centre front and the centre back and chest construction lines.

Table 25

Body measurements															Half increment
Neck	12½″	13″	13½″	14″	14½″	15″	15½″	16″	16½″	17″	17½″	18″	18½″	19″	½″
	31.0	33.2	34.4	35.6	36.8	38.0	39.2	40.4	41.6	43.8	45.0	46.2	47.4	48.6	1.2 cm
Chest	83.5	86.0	88.5	91.0	93.5	96.0	98.5	101.0	103.5	106.0	108.5	111.0	113.5	116.0	2.5 cm
Half across chest	17.75	18.2	18.65	19.1	19.55	20.0	20.45	20.9	21.35	21.8	22.25	22.7	23.15	23.6	0.45
Half across back	18.5	18.8	19.1	19.4	19.7	20.0	20.3	20.6	20.9	21.2	21.5	21.8	22.1	22.4	0.3 cm
Shoulder	12.55	12.7	12.85	13.0	13.15	13.3	13.45	13.6	13.75	13.9	14.05	14.1	14.25	14.4	0.15 cm
Arm length	62.25	62.4	62.55	62.7	62.85	63.0	63.15	63.3	63.45	63.6	63.75	63.9	64.05	64.2	0.15 cm
Depth of scye	19.5	19.8	20.1	20.4	20.7	21.0	21.3	21.6	21.9	22.2	22.5	22.8	23.1	23.4	0.3 cm
Wrist girth	16.3	16.6	16.9	17.2	17.5	17.8	18.1	18.4	18.7	19.0	19.3	19.6	19.9	20.2	0.3 cm

Garment measurements	
Centre back length	88.0 cm Constant
Centre front length	88.0 cm Constant
Back and front line	Constant on classical shirt

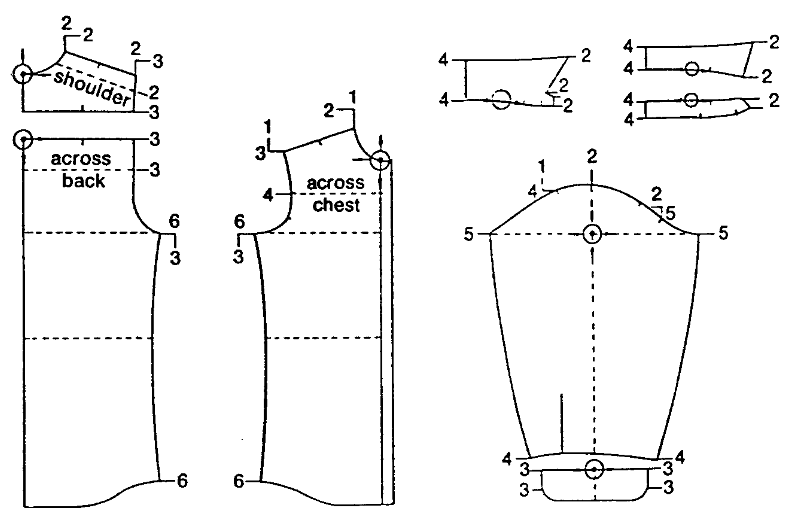


Figure 256 One size shirt grade

Note that the back and front yoke depths are not normally graded, and that the shirt length remains constant.

Figure 257 illustrates the whole graded nest of eight sizes. Divide up the diagonal connecting lines to establish the intermediate sizes.

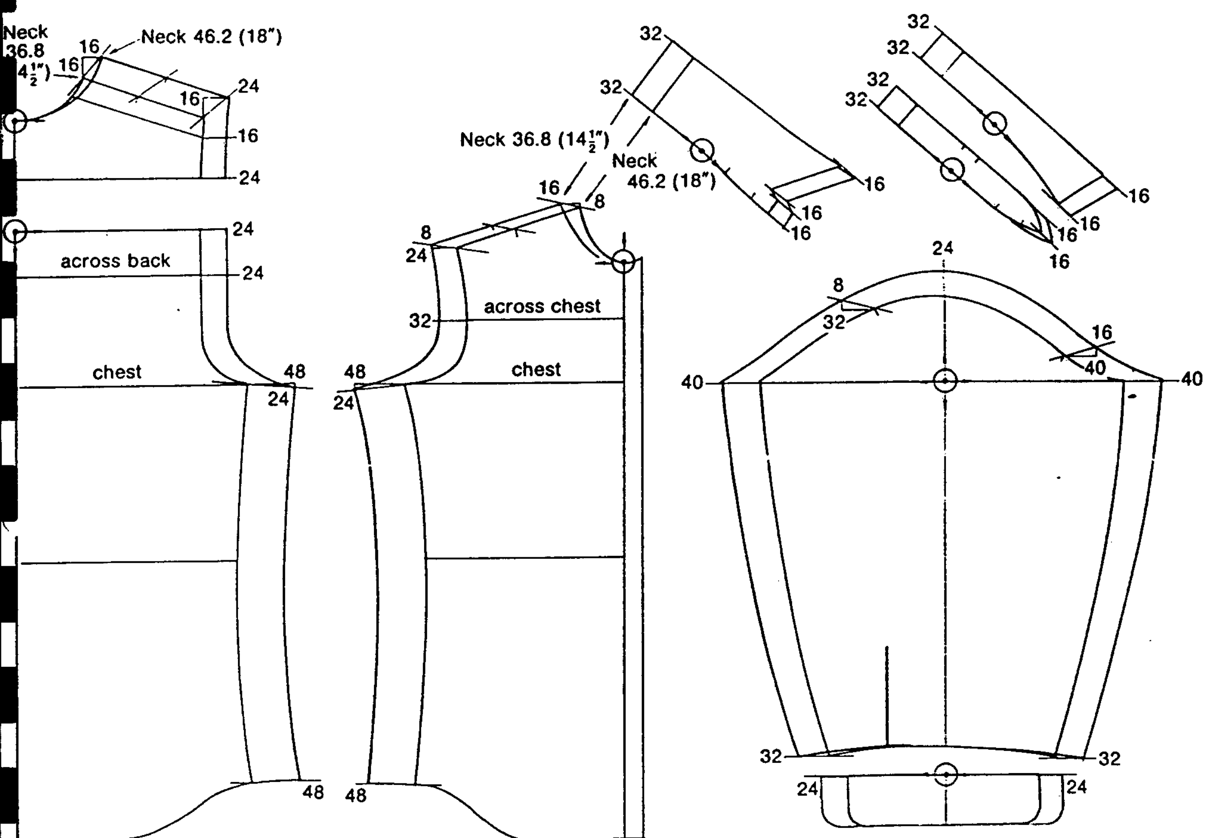
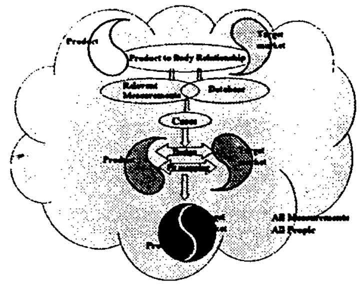


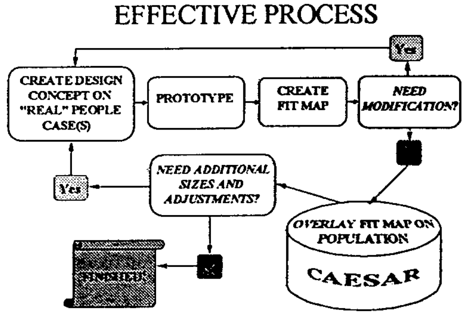
Figure 257 Eight neck size shirt grade from 36.8 cm (14½") to 46.2 cm (18")

Effective Anthropometry Process



Kathleen M. Robinette
March 2000

EFFECTIVE PROCESS



Overview

- Cases
- Fit Mapping Process
- Examples
- Review of Process Adding 3-D
  - New Capabilities
  - New Tools
  - Same Cost

Kathleen M. Robinette
March 2000

Statistics for Anthropometry

Presented at the International Training Workshop on Using Anthropometry for Effective Solutions

by

Kathleen M. Robinette
Air Force Research Laboratory
Human Interface Technology Branch
2255 H Street
Wright-Patterson AFB OH 45433-7022
Phone: (937) 255-8810
Fax: (937) 255-8752
e-mail: kath.robinette@wpafb.af.mil

Overview

- Why Use Statistics?
- Summary Statistics: Things You Have Seen or Will See
- Limitations of Summary Statistics.
- A Better Alternative: Cases

Why Use Statistics?

- Billions of People
- Hundreds of Measurements
- Constant Change
- Need to Simplify

Comparative Stature and Mass Male Military Surveys

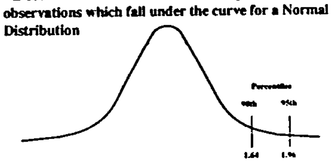
		Mean	SD	N
TURKEY	Stature	169.29	5.73	915
	Mass	64.61	8.23	915
GREECE	Stature	170.51	5.88	1084
	Mass	67.03	9.62	1084
ITALY	Stature	170.60	6.23	1358
	Mass	70.26	[illegible]	1358
GERMANY	Stature	176.88	6.14	1465
	Mass	74.83	8.11	1465
US	Stature	177.34	6.19	2420
	Mass	78.74	9.72	2420

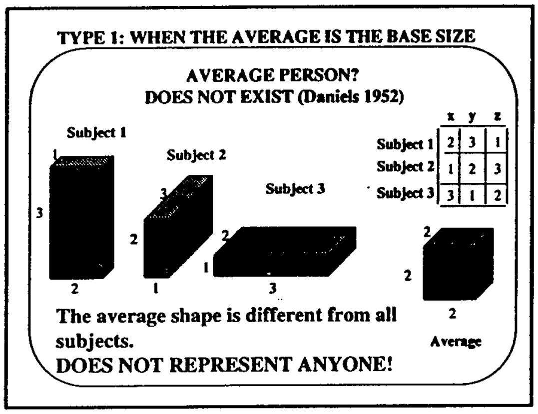
Measures of Central Tendency

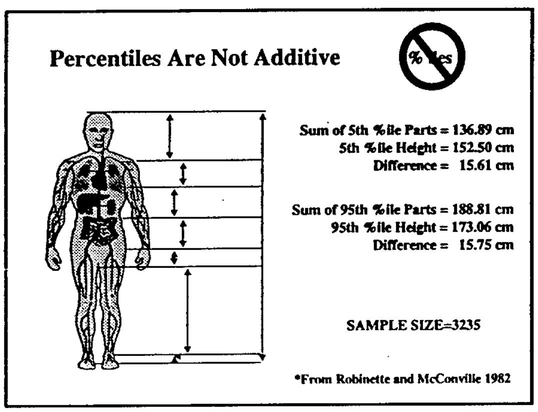
- **Arithmetic Mean (Also called the Average) = sum of all observations divided by the number of observations**
- **Mode = the point with the most observations**
- **Median = the point which divides the observations into equal halves**

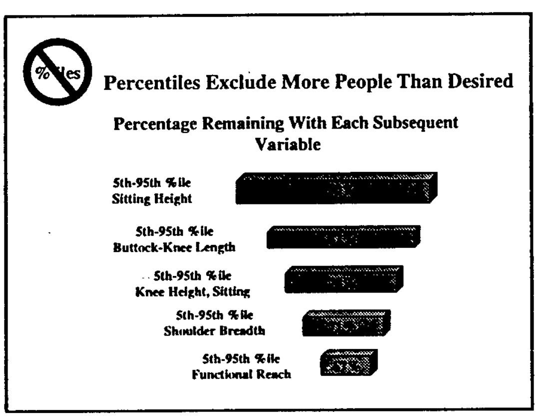
Measures of Location

- **Percentiles: The point at which the stated percentage of the observations are smaller for a single variable**
- **Z-scores: Scores which indicate the percentage of observations which fall under the curve for a Normal Distribution**




TYPE 1: WHEN THE AVERAGE IS THE BASE SIZE
AVERAGE PERSON?
DOES NOT EXIST (Daniels 1952)
Subject 1
Subject 2
Subject 3
x y z
Subject 1 2 3 1
Subject 2 1 2 3
Subject 3 3 1 2
Average
The average shape is different from all subjects.
DOES NOT REPRESENT ANYONE!

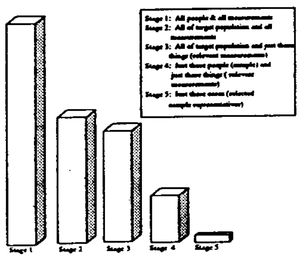

Percentiles Are Not Additive
%iles
Sum of 5th %ile Parts = 136.89 cm
5th %ile Height = 152.50 cm
Difference = 15.61 cm
Sum of 95th %ile Parts = 188.81 cm
95th %ile Height = 173.06 cm
Difference = 15.75 cm
SAMPLE SIZE=3235
*From Robinette and McConville 1982


%iles
Percentiles Exclude More People Than Desired
Percentage Remaining With Each Subsequent Variable
5th-95th %ile Sitting Height
5th-95th %ile Buttock-Knee Length
5th-95th %ile Knee Height, Sitting
5th-95th %ile Shoulder Breadth
5th-95th %ile Functional Reach

HOW BAD CAN THEY BE?
T-1 Aircraft Example

- Aircraft Designed to Accommodate 1st to 99th Percentile Pilots
- Did Not Accommodate 30% of the White Male Pilots, 80% of the Black Male Pilots, and 90% of the Female Pilots for Whom it was designed
- Yoke interference with the thigh resulted from a combination of small and large dimensions
- These combinations are not represented by percentiles

Distillation (Simplification) Process



Anthropometric Cases

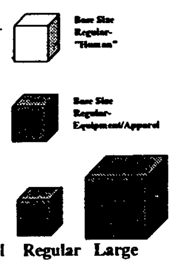
- Cases are combinations of body dimensions.
- Each case is accommodated as a combination.
- Cases can be represented by real people, by computer models, by physical forms, or simply by the combinations of dimensions

Types of Cases

- Central Cases: commonly used in the apparel industry for the starting point (often called the base size)
- Boundary Cases: used in the aerospace and automotive industries (some furniture companies) to verify the "worst cases" are accommodated
- Distributed Cases: used in most industries for accommodation or fit testing

Ergonomic and Apparel "Sizing"

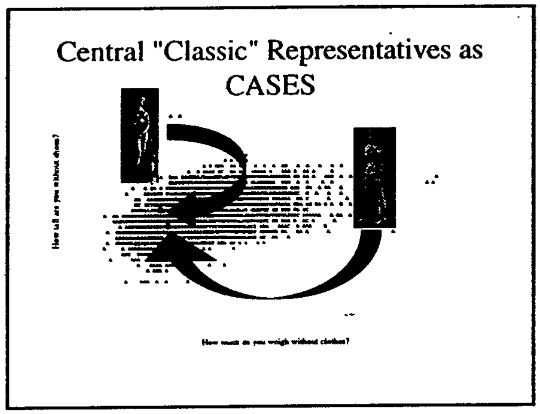
- Base size is selected-2 types
  1 **average**
  2 **a model which is "perfect" size (10 or 12 or 40 regular)**
- Sometimes tried on one person "representing" the base size
- Sizes or layout scaled up and down

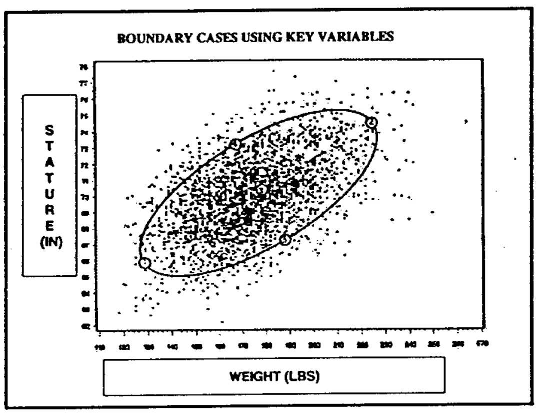


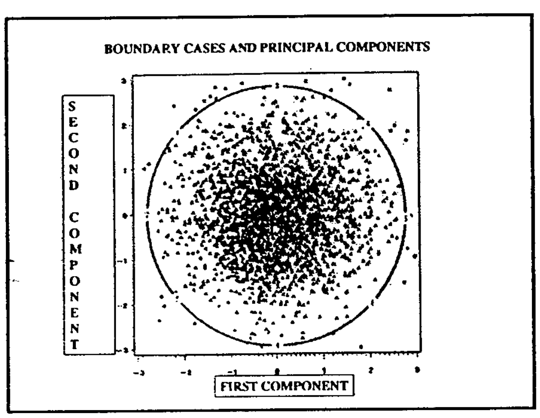
"Perfect" Size "Human" Represents the Case

Perfect Capitoline Style

Perfect Milo Style

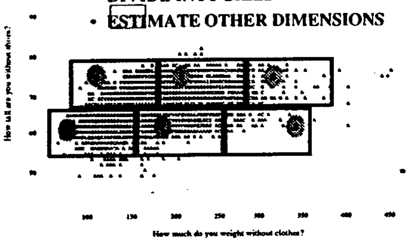

Central "Classic" Representatives as CASES


BOUNDARY CASES USING KEY VARIABLES
STATURE (IN)
WEIGHT (LBS)

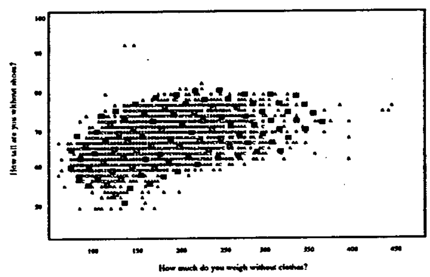

BOUNDARY CASES AND PRINCIPAL COMPONENTS
SECOND COMPONENT
FIRST COMPONENT

TRADITIONAL "ANTHROPOMETRIC" SIZING

- SELECT KEY DIMENSIONS
- DIVIDE INTO SIZES
- ESTIMATE OTHER DIMENSIONS



Distributed Cases



Using Cases in Design and Evaluation

- Design Process Usually Iterative Prototype and Testing
- Best Cases To Use Depend Upon the Product and the Point In The Process
- First Draft Stage A Small Number Usually Best
- Last Test Stage Distributed Real People As Cases Usually Best

Need Raw Data

- Existing Data Sources:
  - Traditional Data CSERIAC: http://www.dtic.mil/iac/iac_dir/CSERIAC.html
  - 3-D Data CARD Lab: http://www.hec.afrl.af.mil/cardlab
- Can also collect your own

CSERIAC DATA EXAMPLES
(Total Number of Surveys is Approx. 40)

- 1959 Survey of Latin American Military
- 1960-61 NATO Anthropometric Survey (Italy, Turkey and Greece)
- 1961 Air Traffic Controllers (USA)
- 1962 The Health Examination Survey Females (USA)
- 1962 The Health Examination Survey Males (USA)
- 1963 The Vietnamese
- 1964 Naval Aviators (USA)
- 1967 Survey of Flying Personnel - Male (USA)
- 1968 German Air Force
- 1968 Survey of Air Force Women (USA)
- 1969 The Imperial Iranian Armed Forces
- 1971 Royal Australian Air Force
- 1971 Survey of Royal Air Force Crewmen (UK)
- 1972 American Airline Stewardesses
- 1972-75 The British Army
- 1974 Canadian Forces Survey
- 1975 Law Enforcement Officers
- 1983 Stereophotometric Anthropometry Males and Females (USA)
- 1988 Navy Females
- 1988 Army Males and Females (USA)
- 1989 Navy Male Flyers
- 1990 Air Force Male Flyers

Still Need Fit Link

- Cases are body proportions not product proportions.
- First iteration of a design is usually based upon some assumptions about the body to product relationship.
- Body to product transforms are calculated through Fit Mapping
- Fit Mapping will be discussed further later in the workshop

Summary

- Statistics are used to simplify the problem and to make decisions.
- Univariate statistics are not appropriate for multivariate problems.
- Multivariate solutions need not be difficult.
- Cases can characterize multivariate relationships simply
- Cases are Body Proportions, Not Product Proportions: Still Need Fit Relationship

ERGONOMICS, 1997, VOL. 40, NO. 2, 189–198

Statistics for a composite distribution in anthropometric studies

MUHAMMAD H. AL-HABOUBI

Systems Engineering Department, King Fahad University for Petroleum and Minerals, Dhahran, Saudi Arabia

Keywords: Anthropometrics; Composite distribution; Statistics; Computer program.

It is a fact that in many countries around the world an international community coexists in a certain country either because of business contracts, such as developing countries (e.g. Saudi Arabia), or due to massive immigration to industrialized countries (e.g. United States). The mixed body of various origins live together and share the same work places. In anthropometric designs, care should be taken to accommodate the user population. When anthropometric statistics and distributions are available for the individual nationals there will not be a need to reinvent the wheel. This study demonstrates a technique to pool the available anthropometric information and use this for designs for the composite population. An algorithm is developed to find pertinent statistics such as the mean, the standard deviation and some percentiles. Formula derivation is possible for the mean and the standard deviation, but because of the complexity of the composite distribution, the percentiles are found by numerical integration. A computer program is prepared to compute these statistics.

1. Introduction

Generally, anthropometric designs are based on the nationals of the country. In today's world, it is rare to find an isolated country. It is a common phenomenon to notice different nationalities living in both industrialized and developing countries. In other words, an international community composed of various ethnic backgrounds exists in many countries. The individual communities contribute to the total population with different proportions, the largest of which probably belongs to the host country. This body of mixed origins may coexist for a substantial number of years, such as those in the contracting business, or even for generations as in the case of immigrants. Therefore, anthropometric designs should not be confined to the natives of the country, but should take into account all the users of a specific man-machine system.

Naturally, anthropometrists rely on relevant data, whether they are the actual data points or a reduced form for a particular design. When the required data are lacking, the obvious way is to collect the pertinent data from the user population. This option was selected for the many nationalities living in Saudi Arabia (Al-Haboubi 1990). However, if the required data are available for each of the participant populations, then the problem is basically to utilize the data in an appropriate way for the design. Available anthropometric studies do not contain the individual data points, for obvious reasons. Instead, some statistics such as the mean, standard deviation and some percentiles are reported. Unfortunately, density functions of body segment dimensions are not typically available in the literature, although they are important. However, it has been generally accepted that the distributions of body

dimensions usually follow the normal distribution (Pheasant 1990). The problem now is to merge the distributions of a particular body dimension for the different nationalities composing the user populations. The purpose of this study is to develop a technique to combine two theoretical distributions belonging to two different populations in a single distribution which is presented graphically. In addition, statistics for the combined population, such as the mean, standard deviation and some percentiles, will be found. This technique could be extended to accommodate three or more populations.

It should be mentioned that the proposed technique is not the first attempt to solve the problem. Jurgens *et al.* (1990) used lower percentiles (i.e. 5th percentile) for the smaller population and larger percentiles for the larger population to represent the required percentiles for the composite population. However, this method underestimates the lower percentile and overestimates the upper percentile and therefore is only approximate.

Roebuck *et al.* (1975, p. 158) described a method to estimate percentiles for the composite population as the sum of the weighted percentiles of the individual populations. The weights are the size percentages contributing to the total size. Although, this method is accurate it requires a search technique of some sort to approach the desired percentile for the composite population. Interpolation is further needed to reach the required estimate. In addition, the method requires percentiles other than those usually found in the literature for the search process. If the individual density functions are not normal then the problem of percentile estimation is considered an obstacle. Percentiles for a normally distributed variable are easily found. Percentiles for other distributions could be estimated by nonparametric estimation methods such as the one based on the kernel-type probability density function (Martz 1978). This method is not appropriate for this study because it assumes the knowledge of the individual data points, which are not usually provided in the literature. Given the availability of data points, one can use the known counting procedure. Moreover, the described method is suitable for a unique mode distribution (Parzen 1962) whereas a composite distribution is most likely to be bimodal. Since the density function of the combined population is expected to be a complex function, which does not coincide with the known theoretical distributions, and since the available methods to estimate the required percentiles have some drawbacks, it was decided to use numerical integration methods in this study. As will be shown later, the estimation of percentiles using numerical integration produces accurate results. It was possible to reach the exact values through derived formulas for the mean and standard deviation of the composite distribution.

2. Problem definition

Given the density functions of a certain random variable X for two populations A and B as $f_A(x)$ and $f_B(x)$, which may or may not follow the same distribution, it is necessary to combine both functions into a composite density function $f_C(x)$ and find the mean, standard deviation and some percentiles for the combined population C. The reason for this could be the need for an anthropometric design involving both populations. The populations could be classified on the basis of sex, age, ethnic background, etc. The random variable X may represent any body dimension relevant to the design, such as stature, sitting height, shoulder breadth, etc. The density functions, $f_A(x)$ and $f_B(x)$, may be modelled by any known continuous distributions such as normal, Weibull, gamma, etc., where the function approaches zero at the far

ends of the x scale. The composite population may contain equal or different proportions of the composing populations A and B. The sizes of each participant population are n_A and n_B, respectively. So, the proportions of population A and B in the composite population are, $P_A = n_A/(n_A + n_B)$ and $P_B = n_B/(n_A + n_B)$, respectively, where $P_A + P_B = 1$. The development of the required statistics for the composite distribution is described below.

2.1. *Percentile*

The function $f_c(x)$ is expected to be complex and analytical integration, for finding the required percentiles, would be rather difficult, if not impossible. Therefore, the method in this study proposes the use of numerical integration such as the Trapezoidal Rule (Cheney 1985). Theoretical distributions may have an infinite range (e.g. the normal distribution) or a finite range (e.g. the triangular distribution). Since the numerical integration process has to start from some point along the x scale, the tail distributions will be assumed to have limits along the x scale where the function approaches zero (e.g. 10^{-10}).

The ranges of X for both populations may be nested or overlapping. The limits of each range are (A_{max}, A_{min}) from population A and (B_{max}, B_{min}) for population B. Since the sorted values of these four limits may take different arrangements, the following conventions are adopted:

(i) The outer limits are Max and Min such that:

$$\text{Max} = \text{maximum}\,\{A_{max}, B_{max}\}$$
$$\text{Min} = \text{minimum}\,\{A_{min}, B_{min}\}$$

(ii) The inner limits L_2 and L_3 are determined once the outer limits are known. The determination of L_2 and L_3 is based on the configuration of the limits as shown in figure 1 such that:

$$\text{Min} \le L_2 \le L_3 \le \text{Max}.$$

The proportions should be used in the density functions to reflect the actual participation of each group as follows:

$$\text{FN}_A(x) = P_A \cdot f_A(x) \text{ and } \text{FN}_B(x) = P_B \cdot f_B(x)$$

The development of the density function for the composite population is as follows:

$$f_C(x) = \begin{cases} \text{FN}_i(x) & \text{for } i = \text{A or B} \quad \text{if } L_3 < x \le \text{Max} \\ \text{FN}_A(x) + \text{FN}_B(x) & \qquad\qquad\qquad\quad \text{if } L_2 \le x \le L_3 \\ \text{FN}_i(x) & \text{for } i = \text{A or B} \quad \text{if Min} \le x < L_2 \end{cases}$$

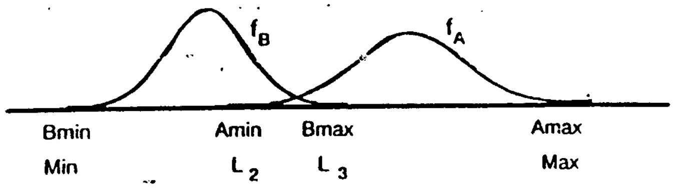
The i subscript is determined once the limits of both functions are computed and the configuration of overlapping or nesting is known.

Suppose that it is required to find a certain percentile (x_p) where p is the percentage corresponding to the area under the curve $f_C(x)$ such that

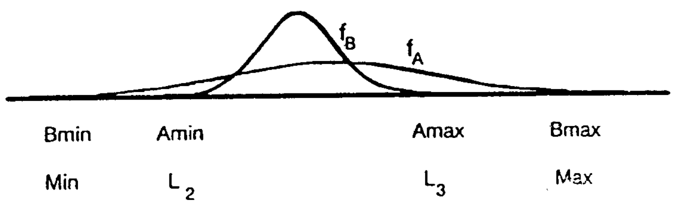
$$\int_{-\infty}^{x_p} f_C(x)\,dx = p.$$

The steps to find x_P by the Trapezoidal rule are:

(i) subdivide the range (Max − Min) into a suitable number of intervals (K), where each interval has a width $H = (\text{Max} - \text{Min})/K$.



(a) f_A and f_B overlaps



(b) f_A and f_B are nested

Figure 1. Different configurations of the density functions f_A and f_B with the outer limits (Max and Min) and the inner limits (L_2 and L_3).

(ii) calculate the area of each trapezoid T_i as:

$$T_i = H/2 \cdot [f_C(x_i) + f_C(x_{i+1})], \qquad i = 1, 2, \ldots, K+1$$

$$x_1 = \text{Min and } x_{i+1} = x_i + H$$

(iii) find $(x_{i+1} | \Sigma T_i = p)$. This x_{i+1} is the required percentile (x_P) for the composite population.

2.2. *Mean*

The mean is found as the sum of the weighted individual means, i.e. $\bar{X}_c = P_A \cdot \bar{X}_A + P_B \cdot \bar{X}_B$ whereas $\bar{X}_j$ is the sample mean for population j, for j = A, B, or C. The proof is as follows:

$\bar{X}_A = (\Sigma x_i)_A / n_A$ and $\bar{X}_B = (\Sigma x_i)_B / n_B$ where x_i is a single data point. Rewriting both equations results in:

$$\bar{X}_A \cdot n_A = (\Sigma x_i)_A \tag{1}$$

and

$$\bar{X}_B \cdot n_B = (\Sigma x_i)_B \tag{2}$$

The mean for the composite population is the sum of all data points divided by the sum of the sample sizes as:

$$\bar{X}_C = \frac{(\Sigma x_i)_A + (\Sigma x_i)_B}{n_A + n_B} \tag{3}$$

substitute (1) and (2) in (3) to get:

$$\bar{X}_C = \frac{(\bar{X}_A \cdot n_A) + (\bar{X}_B \cdot n_B)}{n_A + n_B}$$

or,

$$\bar{X}_C = \bar{X}_A \cdot P_A + \bar{X}_B \cdot P_B$$

This completes the proof.

2.3. *Standard deviation*

The standard deviation of the composite distribution is:

$$\sigma_C = \{P_A \cdot [\sigma_A^2 + (\mu_A - \mu_C)^2] + P_B \cdot [\sigma_B^2 + (\mu_B - \mu_C)^2]\}^{1/2}$$

where μ_i is the mean for population i and σ_i is the variance for population i, for i = A, B, or C. The proof for this formula is as follows:

Consider the variance of the composite distribution,

$$\sigma_C^2 = \int_{-\infty}^{\infty} (x - \mu_C)^2 f_C(x)\,dx$$

Substitute for $f_C(x)$,

$$\sigma_C^2 = \int_{-\infty}^{\infty} (x - \mu_C)^2 [P_A f_A(x) + P_B f_B(x)]\,dx$$

$$= P_A \int_{-\infty}^{\infty} (x - \mu_C)^2 f_A(x)\,dx + P_B \int_{-\infty}^{\infty} (x - \mu_C)^2 f_B(x)\,dx$$

Now consider the first term without P_A, add and subtract μ_A to the term $(x - \mu_c)$, expand the new term, then integrate as follows:

$$\int_{-\infty}^{\infty} (x - \mu_C)^2 f_A(x)\,dx$$

$$= \int_{-\infty}^{\infty} (x - \mu_A + \mu_A - \mu_C)^2 f_A(x)\,dx$$

$$= \int_{-\infty}^{\infty} [(x - \mu_A)^2 + 2(x - \mu_A)(\mu_A - \mu_C) + (\mu_A - \mu_C)^2] f_A(x)\,dx$$

$$= \sigma_A^2 + 2(\mu_A - \mu_C) \int_{-\infty}^{\infty} (x - \mu_A) f_A(x)\,dx + (\mu_A - \mu_C)^2 \int_{-\infty}^{\infty} f_A(x)\,dx$$

$$= \sigma_A^2 + 0 + (\mu_A - \mu_C)^2$$

So, the first term is $P_A[\sigma_A^2 + (\mu_A - \mu_C)^2]$.

Similarly, the second term results in $P_B[\sigma_B^2 + (\mu_B - \mu_C)^2]$. So,

$$\sigma_C^2 = P_A[\sigma_A^2 + (\mu_A - \mu_C)^2] + P_B[\sigma_B^2 + (\mu_B - \mu_C)^2]$$

This completes the proof.

A computer program has been prepared to estimate the above mentioned statistics for the composite population and is given in figure 2.

3. Computer program

A computer code in GW-BASIC for the described technique has been developed to compute the mean, standard deviation and 5th, 50th and 95th percentiles for a combined distribution. In fact, any percentile is obtainable by modifying the code slightly. In addition, the computer program displays a graphical representation of the density function and the cumulative distribution for the combined population. It is to

```
10  DEF FNA(Z)=PA#*
20  DEF FNB(Z)=PB#*
30  DEF FNAB(Z)=FNA(Z)+FNB(Z)
40 DIM X(1000)
50  SUM#=0 : SUM3#=0 : I=1 :SCALE=500 : K=750
60  PER5$="LOST" : PER50$="LOST"  : PER95$="LOST"
70 INPUT "PA=",PA# :INPUT "PB=",PB#
80 INPUT "AMEAN=",AMEAN : INPUT "BMEAN=",BMEAN
90 AMIN=.01 : BMIN=.01 : AMAX=300 : BMAX=300
100 IF FNA(AMIN)>=1E-10 THEN 110 ELSE AMIN=AMIN+.1 : GOTO 100
110 IF FNA(AMAX)>=1E-10 THEN 120 ELSE AMAX=AMAX-.1 :GOTO 110
120 IF FNB(BMIN)>=1E-10 THEN 130 ELSE BMIN=BMIN+.1 :GOTO 120
130 IF FNB(BMAX)>=1E-10 THEN 140 ELSE BMAX=BMAX-.1 :GOTO 130
140 IF AMAX>=BMAX THEN MAX=AMAX:L3=BMAX:U$="A" ELSE MAX=BMAX:L3=AMAX:U$="B"
150 IF AMIN<=BMIN THEN MIN=AMIN:L2=BMIN:L$="A" ELSE MIN=BMIN:L2=AMIN:L$="B"
160 H=(MAX-MIN)/K: X(1)=MIN
170 IF MIN<=X(I) AND X(I)<L2 THEN IF L$="A" THEN GOSUB 440 ELSE GOSUB 460
180 IF L2<=X(I) AND X(I)<=L3 THEN FX1#=FNAB(X(I)) : FX2#=FNAB(X(I)+H)
190 IF L3<X(I) AND X(I)<=MAX THEN IF U$="A" THEN GOSUB 440 ELSE GOSUB 460
200 C%=FX2#*SCALE : IF C% < 1 THEN 230
210 LPRINT USING "###.#" ; X(I); :LPRINT "  ";
220 FOR J=1 TO C% : LPRINT "+"; : NEXT J : LPRINT
230 T#=H/2*(FX1#+FX2#) : SUM#=SUM#+T#
240 XI#=X(I)^2  :  XIH#=(X(I)+H)^2
250 T3#=  XI# * FX1#  +  XIH# * FX2#
260 SUM3#=SUM3#+T3#
270 IF SUM# >=.05 AND PER5$="LOST" THEN P5=X(I)+H    :PER5$="FOUND"  :GOTO 300
280 IF SUM# >= .5 AND  PER50$="LOST" THEN P50=X(I)+H :PER50$="FOUND":GOTO 300
290 IF SUM# >= .95 AND PER95$="LOST" THEN P95=X(I)+H :PER95$="FOUND":GOTO 300
300 I=I+1
310 X(I)=X(1)+(I-1)*H
320 IF X(I) <  MAX GOTO 170
330 MEAN=PA#*AMEAN+PB#*BMEAN
340 SUM3#=H/2* SUM3#
350 SD#=SQR(SUM3#-MEAN^2)
360  PRINT"STATISTICS FOR THE COMPOSITE POPULATION A AND B"
370  PRINT"-----------------------------------------------"
380  PRINT "THE MEAN= ";  :PRINT USING "###.#";MEAN
390  PRINT "THE STANDERD DEVIATION="; : PRINT USING "##.#";SD#
400  PRINT"THE 5th  PERCENTILE="; :PRINT USING "###.#";P5
410  PRINT"THE 50th PERCENTILE="; :PRINT USING "###.#";P50
420  PRINT"THE 95th PERCENTILE="; :PRINT USING "###.#";P95
430 STOP
440 FX1#=FNA(X(I)):FX2#=FNA(X(I)+H)
450 RETURN
460 FX1#=FNB(X(I)):FX2#=FNB(X(I)+H)
470 RETURN
480 END
```

Figure 2. A listing of the computer program.

be noted that the x range may not be completely shown since the values of $f_c(x)$ at the far ends of x are very small. However, these small values tend to be crucial in providing accurate estimates of the statistics.

In order to use the program, it is necessary to assign the individual density functions for both populations A and B to the functions $FN_A(Z)$ and $FN_B(Z)$, respectively, where Z is a body dimension variable. The assignment of the labels A or B to a particular distribution is immaterial, from the user point of view. Also, the program requires values of the means (i.e. A_{mean} and B_{mean}), the standard deviations SD_A and SD_B and the proportions P_A and P_B. The program computes the limits of x for density functions with two tails and with finite ranges. Distributions with one tail such as the exponential function, or no tails such as the uniform function, are unlikely to represent anthropometric variables. The program determines the configuration of the ranges by using U$ and L$ logic variables, then carries out the numerical integration computations and prints the composite density function and the composite cumulative distribution. Computations of the mean and the standard deviations are based on the derived formulas.

All important arithmetic operations are carried out in double precision (indicated

Table 1. Statistics from the computer program over various K intervals for two identical density functions following $N \sim (170, 3)$.

K	MEAN	S.D.	5th	50th	95th	Sum of errors
50	170·0	3·0	165·420	170·002	175·347	0·769
100	170·0	3·0	165·420	170·002	174·965	0·387
150	170·0	3·0	165·165	170·002	175·093	0·259
200	170·0	3·0	165·229	170·002	174·965	0·196
250	170·0	3·0	165·114	170·002	175·042	0·158
300	170·0	3·0	165·165	170·002	174·965	0·132
350	170·0	3·0	165·092	170·002	175·020	0·114
400	170·0	3·0	165·133	170·002	174·965	0·100
450	170·0	3·0	165·080	170·002	175·008	0·090
500	170·0	3·0	165·114	170·002	174·965	0·081
550	170·0	3·0	165·073	170·002	175·000	0·074
600	170·0	3·0	165·101	170·002	174·965	0·069
650	170·0	3·0	165·067	170·002	174·936	0·005
700	170·0	3·0	165·092	170·002	174·965	0·059
750	170·0	3·0	165·114	170·002	174·940	0·056
800	170·0	3·0	165·086	170·002	174·965	0·053
850	170·0	3·0	165·105	170·002	174·943	0·050
900	170·0	3·0	165·080	170·002	174·965	0·047
950	170·0	3·0	165·098	170·002	174·945	0·045
1000	170·0	3·0	165·076	170·002	174·965	0·043

by #) to increase the accuracy of the estimates. It should be noted that P_A and P_B are treated as double precision variables in the $FN_A(Z)$ and $FN_B(Z)$ functions so that the returned values of these functions have the same degree of precision. To improve accuracy further, an attempt was made to determine the appropriate number of intervals (K) to be used. The computer program was executed having two identical normal distributions to represent a certain body dimension for two populations with a mean of 170·0 (cm) and a standard deviation of 3·0. These values were hypothetical and reasonable for stature in centimetres and selected merely to check the accuracy of the program. The proportion of each population was chosen to be 0·5. Accordingly, the composite density function was found to be normal with a mean of 170·0, standard deviation of 3·0. 5th percentile of 165·065, 50th percentile of 170·0 and 95th percentile of 174·935. These exact statistics for the composite population are compared with their counterparts obtained by the computer program over various numbers of intervals ranging between 500 and 9500. The sum of the absolute errors for all three statistics was computed at each trial and the output of the computer run is summarized in table 1. As can be seen, percentiles by the two methods compare closely and the absolute errors are small. The largest sum of absolute errors (i.e. 0·081 cm) is negligible whereas the best run produced an absolute error of 0·005. These errors are quite acceptable for anthropometric designs and therefore the trapezoidal rule is considered to be adequate. The general trend of the sum of absolute errors decreases as the number of intervals increases. This trend was observed by testing other normal functions. The values of the absolute errors seem to stabilize to the lowest value as the number of iterations increase, indicating a balance between the truncation error and the round-off error. Accordingly a large value of K should be selected (say 8,000) to reduce the total error. However, to obtain a curve for the composite density function a scale factor (SCALE = 500) and 100 intervals were found suitable for presentation on A4 paper.

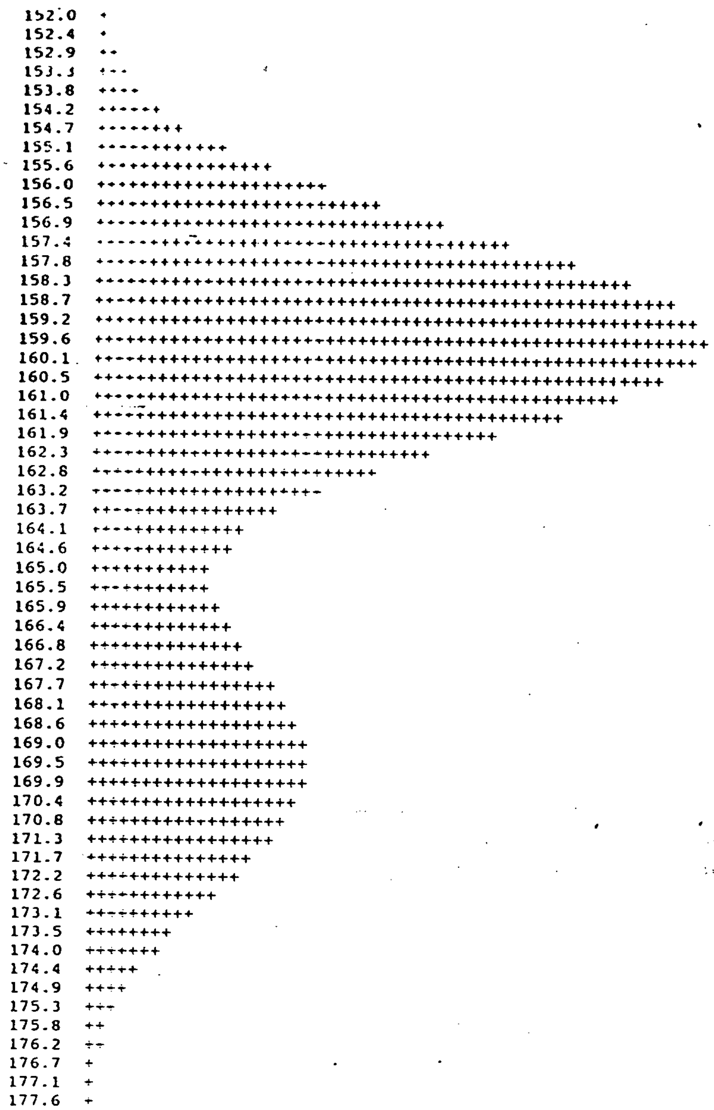


Figure 3. Density function for the composite population in the example.

A listing of the computer program is shown in figure 2. The variables used in the program match those described above. Some of the variables, not mentioned above, are self-explanatory.

3.1. *Example*

Suppose that the stature of two population A and B is normally distributed with N_A (170, 3) and N_B (160, 2·5), where dimensions are in centimetres and the size proportions are $P_A = 0{\cdot}3$ and $P_B = 0{\cdot}7$. The estimates from the computer programs rounded to the nearest decimal point ($K = 8000$) are found

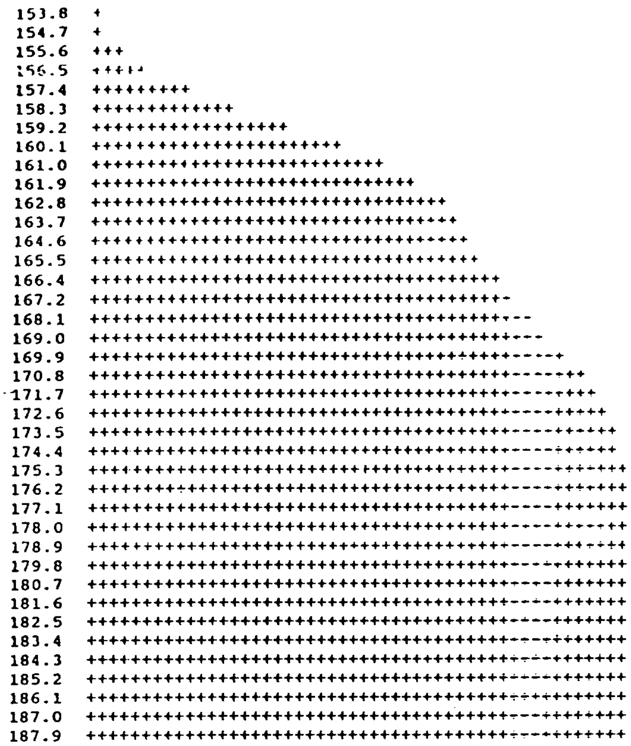


Figure 4. Cumulative distribution for the composite population in the example.

to be:

$$\text{Mean} = 163{\cdot}0$$

$$\text{Standard deviation} = 5{\cdot}3$$

$$\text{5th percentile} = 156{\cdot}4$$

$$\text{50th percentile} = 161{\cdot}4$$

$$\text{95th percentile} = 172{\cdot}9$$

The shape of the composite density function appears in figure 3, and the cumulative distribution is shown in figure 4.

4. Conclusion

Anthropometrists should tailor their designs for the user population, which may be a heterogenous group of different origins, sexes, age groups, or other classification. Obviously, the designs must be based on relevant anthropometric data in some form. If such data do not exist, then the designer should collect the required data from among the prospective users. However, if independent data are collected for the various categories comprising the user population, there is no need for re-collection. It is better to devise a technique to pool the individual forms of data. This paper presents an algorithm to merge the density functions of any body dimension for two populations. The method developed has been tested by a computer program and checks well for practical applications of some statistics. The method will be extended

to accommodate more than two populations and will be applied to a real life situation. The work presented in this paper is not unique to anthropometric studies and may be utilized in other scientific areas.

Acknowledgement

The author would like to acknowledge research support from the Department of Manufacturing Engineering and Operations Management, University of Nottingham and from King Fahd University of Petroleum & Minerals.

References

Al-Haboubi, M., 1990, Anthropometric Study for the user population in Saudi Arabia. In, Y. Queinnec and F. Daniellon (eds), *Designing for Everyone. Proceedings of the 11th Congress of the International Ergonomic Association*, Paris (Taylor and Francis, London), 891–893.

Cheney, W. and Kincaid, D., 1985, *Numerical Mathematics and Computing* (Brooks Cole, Monterey, CA).

Hines, W. W. and Montgomery, D. C., 1990, *Probability and Statistics in Engineering and Management Science* (Wiley, New York).

Jurgens, H. W., Aunc, I. A. and Pieper, U., 1990, *International data on anthropometry*, Occupational Safety and Health Series, No. 65 (International Labour Office, Geneva).

Martz, H. F., 1978, Estimating Percentiles of non-normal anthropometric populations, Final report, *Proceedings of the Human Factors Society, 22nd Annual Meeting*, 16–19 October, Detroit, Michigan, 445–449.

Parzen, E., 1962, On estimation of a probability density function and mode, *Annals of Mathematical Statistics*, 33, 1065–1076.

Pheasant, S., 1990, *Body Space: Anthropometry, Ergonomics and Design* (Taylor and Francis, London).

Roebuck, J. A., Kroemer, K. H. E. and Thomson, W. G., 1975, *Engineering Anthropometry Methods* (Wiley, New York).

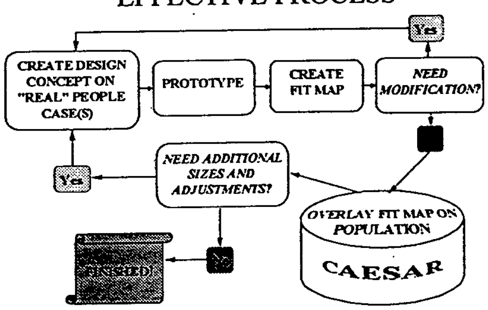
Anthropometric Fit Mapping

Presented at the International Training Workshop on Using Anthropometry for Effective Solutions

by

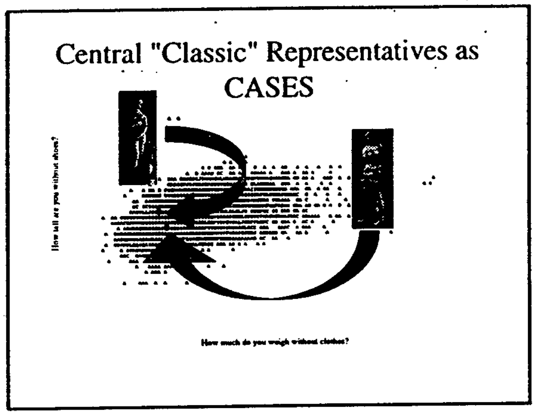
Kathleen M. Robinette
Air Force Research Laboratory
Human Interface Technology Branch
2255 H Street
Wright-Patterson AFB OH 45433-7022
Phone: (937) 255-8810
Fax: (937) 255-8752
e-mail: kath.robinette@wpafb.af.mil

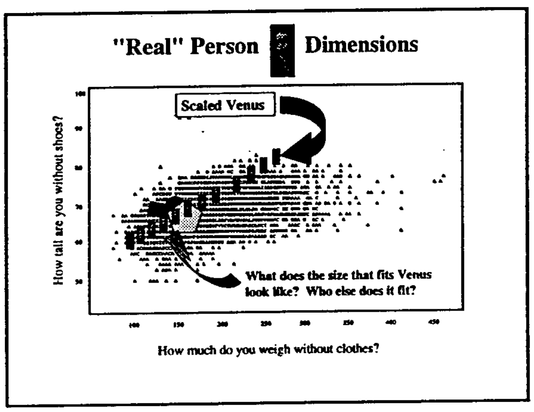
EFFECTIVE PROCESS

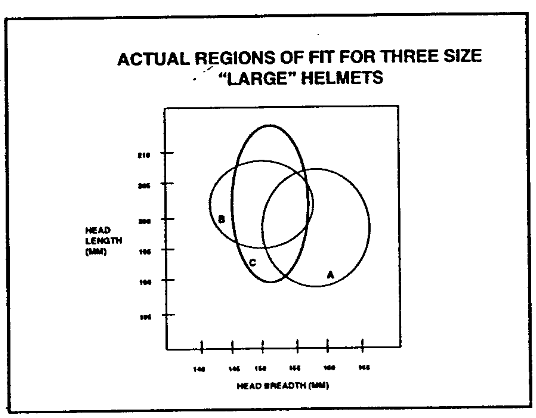


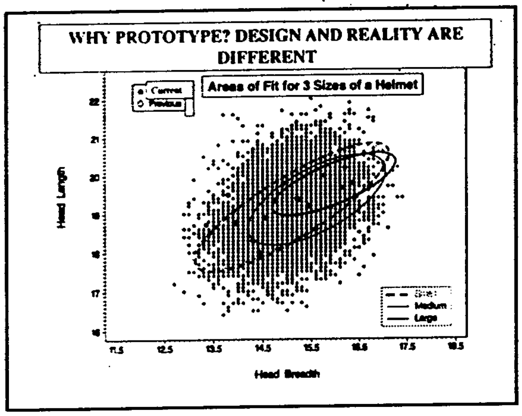
Using Anthropometry in the Process

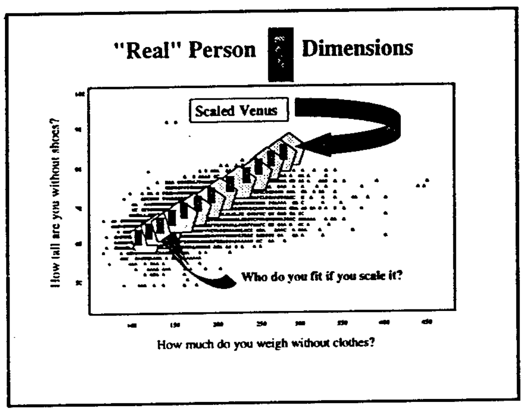
- Design
- Prototyping
- Mapping

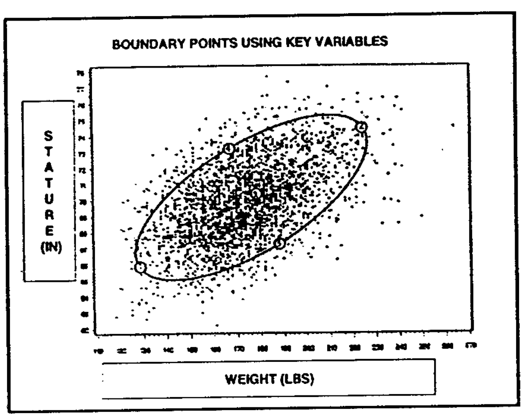

Central "Classic" Representatives as CASES

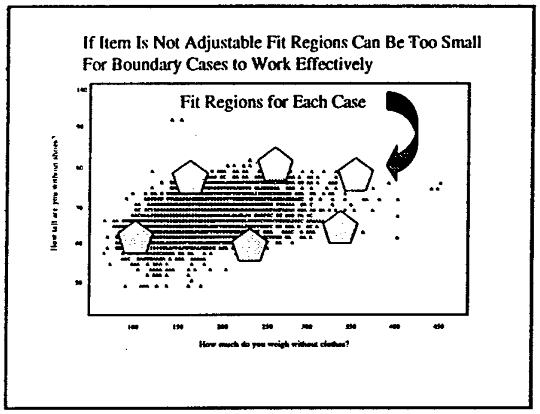

"Real" Person Dimensions
Scaled Venus
What does the size that fits Venus look like? Who else does it fit?
How tall are you without shoes?
How much do you weigh without clothes?

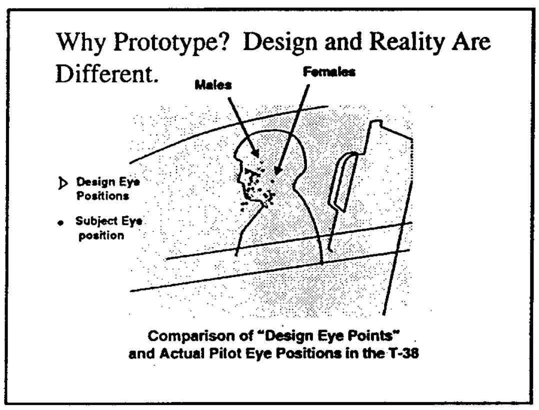

ACTUAL REGIONS OF FIT FOR THREE SIZE "LARGE" HELMETS
HEAD LENGTH (MM)
HEAD BREADTH (MM)
B
C
A

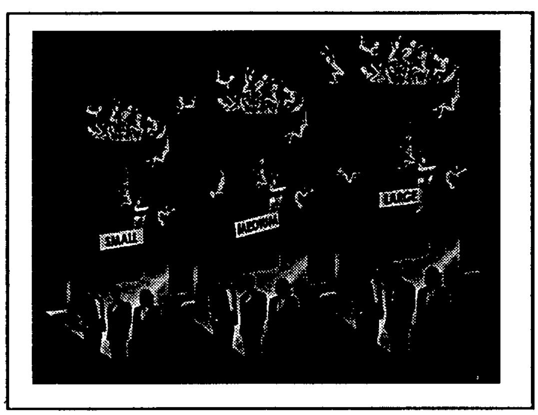

WHY PROTOTYPE? DESIGN AND REALITY ARE DIFFERENT
Areas of Fit for 3 Sizes of a Helmet
Head Length
Head Breadth
Medium
Large


"Real" Person
Dimensions
Scaled Venus
Who do you fit if you scale it?
How tall are you without shoes?
How much do you weigh without clothes?


BOUNDARY POINTS USING KEY VARIABLES
STATURE (IN)
WEIGHT (LBS)


If Item Is Not Adjustable Fit Regions Can Be Too Small
For Boundary Cases to Work Effectively
Fit Regions for Each Case
How tall are you without shoes?
How much do you weigh without clothes?


Why Prototype? Design and Reality Are Different.
Males
Females
Design Eye Positions
Subject Eye position
Comparison of "Design Eye Points"
and Actual Pilot Eye Positions in the T-38


SMALL
MEDIUM
LARGE

What is Fit Mapping?

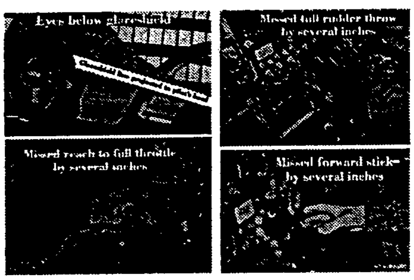
Use Live Subjects to Determine the Relationship Between Fit and Anthropometry

- Quantitative Measure(s) of Fit
- Anthropometric Measures of Subjects
- Measure and Statistically Quantify the Relationship
- Determine the anthropometric point at which the product no longer fits

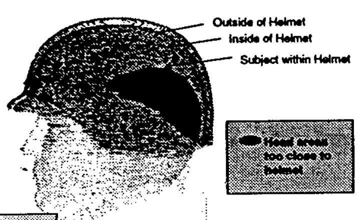
Measure Fit + Performance in Aircraft

Case 7 for Joint Primary Air Training System (JPATS) in the T-38

with inertia reels locked

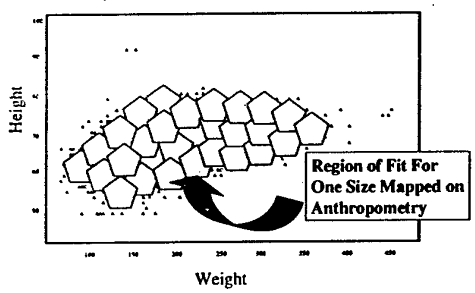


Fit Mapping a Helmet

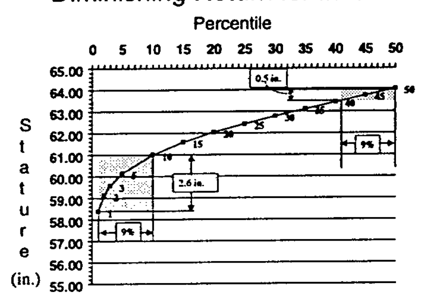


Fit Assessment Failure
- Comfortable
- Stable
- Subject Can Perform Tasks
- Not Safe Ballistically

Fit Mapping Optimizes The Accommodation To Your Population Or Market



Diminishing Return for Investment

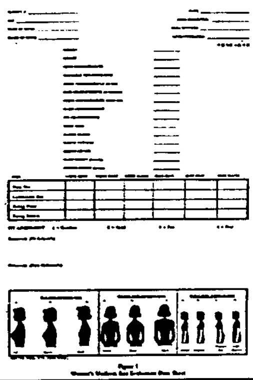


Example of Fit Mapping Navy Women's Uniform*

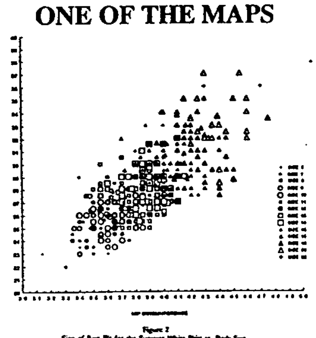
- Fit Tested With Existing Uniform
- Mapped Fit to Anthropometry in General
- Mapped Fit on Sample of Population
- Determined Unneeded Sizes
- Determined New Size Ranges

* From Mellian, S.A., Ervin, C. and Robinette, K.M. (1990) and Robinette, K.M., Mellian, S. and Ervin, C. (1990)

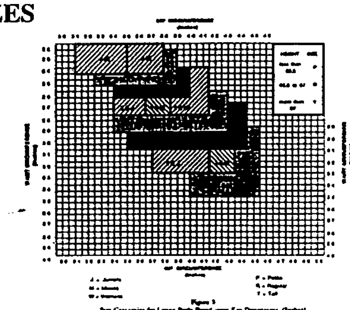
ASSESSMENT FORM



ONE OF THE MAPS



NEW SIZES



RESULTS

Went From 75% Needing Alterations to Less Than 1%

99% Received the Size of Best Fit the First Time Based Upon the Size Prediction Chart

Same Number of Sizes Used

SUMMARY
FIT MAPPING METHOD

- QUANTIFIES THE LINK BETWEEN BODY SIZE AND EQUIPMENT SIZE
- ESTABLISHES GOOD ITEM PROPORTIONING
- ESTABLISHES RANGE OF FIT PER SIZE
- MINIMIZES NUMBER OF ADJUSTMENTS & SIZES

Crew Station Application

Presented at the International Training Workshop on Using Anthropometry for Effective Solutions

Gregory F. Zehner
Kathleen M. Robinette*

*Air Force Research Laboratory
Human Interface Technology Branch
2255 H Street
Wright-Patterson AFB OH 45433-7022
Phone: (937) 255-8810
Fax: (937) 255-8752
e-mail: kath.robinette@wpafb.af.mil

PROJECT OVERVIEW: PURPOSE

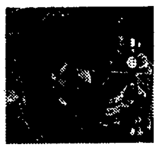
- FIND UPPER AND LOWER BODY SIZE LIMITS FOR EACH AIRCRAFT.
- DETERMINE THE PERCENTAGE OF THE POPULATION THAT FITS IN EACH AIRCRAFT.
- IDENTIFY COCKPIT FEATURES THAT CAUSE ACCOMMODATION PROBLEMS.

PROJECT OVERVIEW: QUESTIONS

- CAN THE USAF SAFELY CHANGE AFI 48-123? (1 INCH = 20% GAIN FOR FEMALE POPULATION)
- SHOULD THE USAF CHANGE OVERALL ENTRANCE REQUIREMENTS, OR ONLY REQUIREMENTS FOR CERTAIN AIRCRAFT?
- CAN AIRCRAFT BE MODIFIED TO IMPROVE ACCOMMODATION FOR A REASONABLE PRICE?

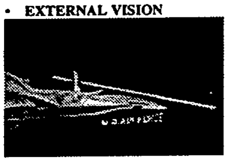
PROJECT OVERVIEW: APPROACH

- ESTABLISH OPERATIONAL REQUIREMENTS FOR THE AIRCRAFT.
- MEASURE UP TO 25 SUBJECTS IN THE COCKPIT.
- ANALYZE DATA TO FIND ANTHRO LIMITS AND ACCOMMODATION PERCENTAGES.



DATA GATHERING: MEASUREMENTS

SMALL PILOTS:
- REACH TO HAND CONTROLS
- REACH TO RUDDER PEDALS
- EXTERNAL VISION



LARGE PILOTS:
- OVERHEAD CLEARANCE
- VISION TO INSTRUMENTS
- EJECTION CLEARANCES OF THE KNEES AND TORSO
- OPERATIONAL LEG CLEARANCES WITH THE INSTRUMENT PANEL
- OPERATIONAL LEG CLEARANCE WITH THE STICK MOTION ENVELOPE

DETERMINING OPERATIONAL REQUIREMENTS

- REVIEW AIRCRAFT T.O.-1 FOR CONTROLS AND EMERGENCY PROCEDURES.
- INTERVIEW PILOTS.
- CONDUCT SIMULATOR FLIGHTS TO TEST EMERGENCY PROCEDURES.
- CONDUCT STUDY FLIGHTS TO FIND VISION REQUIREMENTS.
- WRITE DRAFT REQUIREMENTS.
- SEND QUESTIONNAIRES ON DRAFT REQUIREMENTS TO PILOTS.
- UPDATE DRAFT REQUIREMENTS, AND SEND TO USER COMMAND FOR REVIEW AND SIGNATURE.

T-38 OPERATIONAL REQUIREMENTS
(SIGNED BY AETC/CC)

1. VISION TO SEE BASE OF PITOT AND ALL HUD SYMBOLOGY

2. FULL RUDDER AND BRAKE

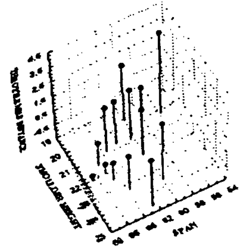
3. REACH TO THE FOLLOWING WITH LOCKED REELS:
   - THROTTLES
   - EJECTION HANDLE
   - INERTIAL REEL LOCK

JPATS Cases

Table 1: Multivariate Cases 1 - 7

	Case 1	Case2	Case 3	Case 4	Case 5	Case 6	Case 7
Thumb tip reach	27.0	27.6	33.9	28.7	35.6	36.0	26.1
Buttock-knee length	21.3	21.3	25.5	22.7	27.4	27.9	20.8
Knee-height sitting	18.7	19.1	23.3	20.6	24.7	24.8	18.1
Sitting height	32.8	35.5	34.8	38.5	40.0	38.0	31.0
Eye height sitting	28.0	30.7	30.2	33.4	35.0	32.8	26.8
Shoulder height sitting	20.6	22.7	22.6	25.2	26.9	25.0	19.5
Shoulder breadth range	14.7-18.1	[illegible]	16.2-21.2	16.8-21.7	16.9-22.6	16.8-22.5	14.2-18.0
Chest depth range	7.4-10.9	[illegible]	7.2-11.3	7.1-11.0	7.3-12.1	7.4-12.2	7.2-10.2
Thigh circumference range	18.5-25.0	[illegible]	20.2-27.6	17.6-26.3	18.6-29.2	19.1-29.7	17.8-25.2

3-D Map of Throttle Miss Distance



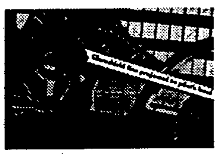
T-38 RESULTS
MIN. SPAN = 66.5"

- REACH TO RETRACT FULL THROTTLES
- INERTIAL REELS LOCKED
- REPRESENTS WORSE CASE CONDITIONS

EXCLUDES
60% JPATS FEMALES
2% JPATS MALES
23% FEMALE PILOTS
1% MALE PILOTS

CASE 7 MISSES BY INCHES

T-38 VISION
MIN. EYEHT=29.75"



- -11 DEGREES ONV.
- ORIGINAL DESIGN EYE LINE
- BASE OF PITOT TUBE + HUD DESIGN EYE?
- VERIFIED WITH STUDY FLIGHTS

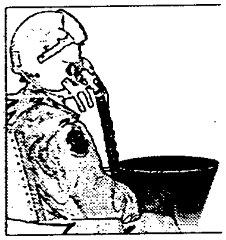
EXCLUDES:
- 58% JPATS FEMALES
- 10% JPATS MALES
- 14% FEMALE PILOTS
- 6% MALE PILOTS
- CASE 7 IS SEVERAL INCHES TOO LOW

T-38 RUDDERS
MIN LEG = 43"

- BASED ON FULL RUDDER AND FULL BRAKE - FULL UP
- PILOT TIGHTLY RESTRAINED
- BLOWN TIRE ON LANDING

EXCLUDES
- 54% JPATS FEMALES
- 5% JPATS MALES
- 19% FEMALE PILOTS
- 3% MALE PILOTS
- CASE 7 MISSES BY INCHES

T-38
STICK THROW PROBLEMS



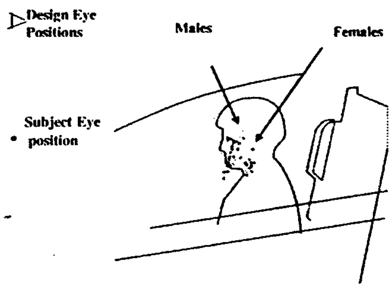
- HALF OF OUR TEST SUBJECTS HAD STICK CLEARANCE PROBLEMS FULL-UP.
- PROBLEMS INCREASE IF WE :
- RAISE THE PILOT
- MOVE THE PILOT FORWARD

T-38
OVERHEAD CLEARANCE
(AFT COCKPIT)

- 40 INCH SITTING HEIGHT WILL HIT CANOPY - DEPENDING ON HELMET FIT AND POSTURE
- HOW MUCH CLEARANCE SPACE IS NEED FOR -G FLIGHT?

T-38C-HUD FOV

- LARGE PILOTS MUST LEAN FORWARD FOR IFOV
- 5% (1950) MALE PILOT JUST SEES -11 ONV LINE AND HUD
- SPO STILL WORKING DESIGN EYE ISSUE - MORE INVOLVED THAN ANTHRO



Comparison of "Design Eye Points" and Actual Pilot Eye Positions in the T-38

Using Maps to Modify

- Have Quantified Information
- Use to Modify Either Crew Selection Criteria or System
- For T-1 Used to Modify the System Prior to Purchase
- Result Accommodated 99 % of men and 95% of women of all races
- Up from 70% of white men, 20% of black men and 10% of women

Wednesday, 29 March 2000

3-D Solutions
by Kathleen Robinette

CAESAR - 3D Anthropometry Survey
by Kathleen Robinette

Cleopatra®: A Database Management for CAESAR
by Marc Rioux

3D Body Scanners
by Marc Rioux

PolyWorks®
by Marc Rioux

3-D Solutions

Presented at the International Training Workshop on Using Anthropometry for Effective Solutions

by

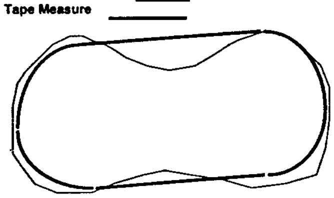
Kathleen M. Robinette
Air Force Research Laboratory
Human Interface Technology Branch
2255 H Street
Wright-Patterson AFB OH 45433-7022
Phone: (937) 255-8810
Fax: (937) 255-8752
e-mail: kath.robinette@wpafb.af.mil

WB4 Whole Body Scanner (Cyberware)

- **Scans the entire surface of the body**
- **4 scanning heads**
- **2 m high**
- **1.2 m diameter**
- **17 sec**
- **Resolution = 2.16 mm**

Two Bust Circumference Measures:

Scanned Measure
Tape Measure

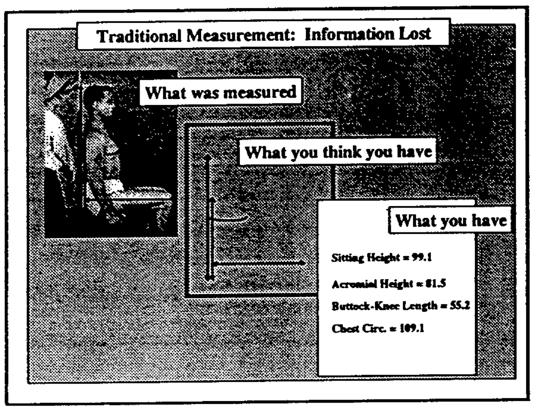


Tape pulls in skin and misses detail
Scan does not contact skin and gets minute detail

Traditional Anthropometry

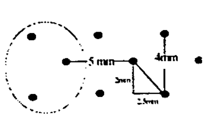
Limitations
- 1-D
- Disconnected measurements
- Inability to measure fit
- Limited orientation
- No contour information
- Slow for large surveys

Advantages
- Portable
- Inexpensive
- Widespread availability of tools
- Measure areas not visible to the scanner
- Accuracy within 1 mm



Scanning

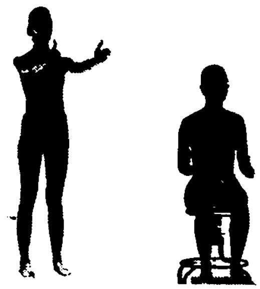
Limitations
- Not easily portable
- Expensive
- Space requirement
- Must control lighting
- Measurement restrictions
- Resolution = 3.2 mm



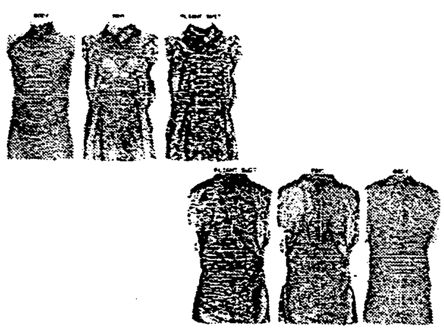
Advantages
- 3-D
- Captures shape, contour, curvature, surface area, and volume
- Measures fit geometry
- Data reoriented
  - New data after subject leaves
- More consistent measures (maximums, minimums)

Obstruction

- Shading
  - arms
  - legs
  - torso
- Missed Data
  - flat surfaces



Measuring the Geometry of Fit



Design Effectiveness Improvement with 3-D Data Bases Such as CAESAR

- **Can Use Univariate CAESAR Measurements and Existing Design Methods**
- **Can Use 1-D and 3-D Measurements to Select Representative CASES**
- **3-D Models From CAESAR Can Help:**
  - **Create Solid Objects Using Milling or SLA**
  - **Create Computer Models for CAD**
  - **Evaluate Accuracy of Computer Models Already in Use**

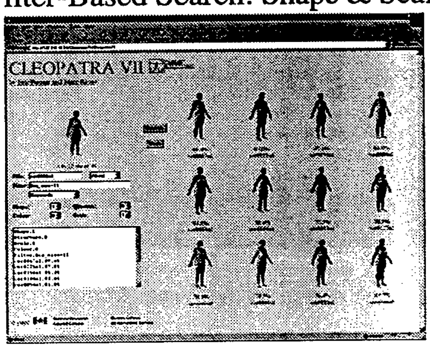
Using CAESAR in Design Concept

- Use Random Sample of CAESAR as CASES
- Use Subjects Around a CAESAR Ellipsoid as CASES
- Use Subject(s) Near CAESAR Center for Key Measurements or With "Characteristic" Shape as CASES
- Use Subjects Distributed in Ellipsoid as CASES

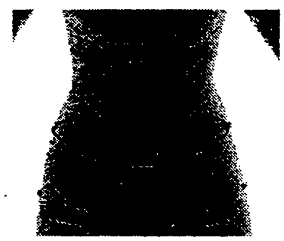
Using CAESAR in Design Concept

- Find CASES:
  - Statistica/Excel or Similar Software if 1D
  - CLEOPATRA if 3D and 1D
- Extract New Measurements from 3-D Scans for CASE Selection or For Input into Existing Models.
- Input measures for each CASE into your existing models or create a 3D model
  - Computer models of CASES with prototype overlay in INTEGRATE
  - Computer solid model in POLYWORKS or INTEGRATE

Filter-Based Search: Shape & Scale



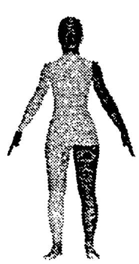
Extract New Additional Measures Using Integrate



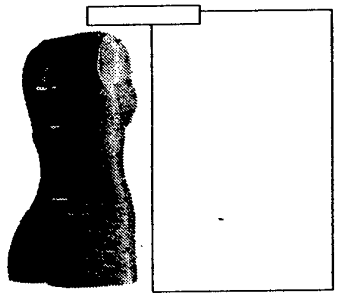
Prototype

- Can Use an Existing Item(s) That Is Similar If The Difference Can Be Adjusted For in The Fit Evaluation
- Can Use Current Practice with or without CAESAR size or shape adjustment
- Can Use CAESAR Data for Solid Models Around Which to Prototype.
  - Numerically Controlled Milling
  - Stereolithography

Single-Object Operations

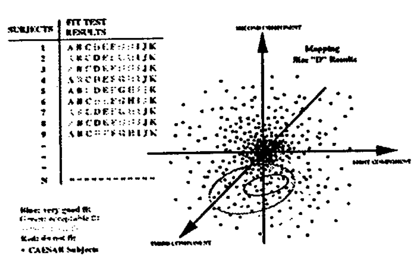


Solid Model for Dress Form



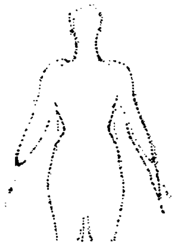
3-D Electronic Models of Cases

Mapping Fit Tests on Shape Descriptors Components



Multi-Object Operations

Front Profiles Male, Female



Multi-Object Operations

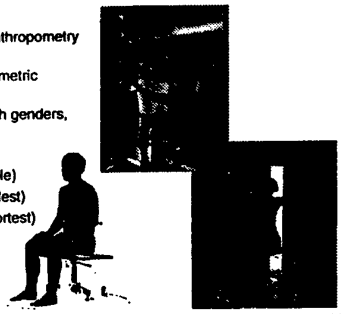
Side Profiles Male, Female

Solutions in 3-D: Future Possibilities

- 3-D Design Models/CASES makes designing faster, and more accurate.
- 3-D Prototyping makes design closer to product.
- 3-D Fit Mapping adds ability to visualize and measure the geometry of the relationship
- Can find the Best Measurements For Predicting Who Will Fit and Who Will Not AFTER The Fit Assessment
- Can Find and Accommodate Shape Measurements
- BEST FIT AT CHEAPEST COST IN LEAST TIME

CAESAR™ Civilian American and European Surface Anthropometry Resource

- First 3-D Surface Anthropometry of NATO
- Represent anthropometric variability
  - age (18-65), both genders, ethnicity
- 9,000 subjects
  - U.S. (most people)
  - Netherlands (tallest)
  - Italy (among shortest)



BENEFITS

Military

- Why civilian? New roles for women [illegible] requires body size data for [illegible] potential population of people [illegible]
- Design for interoperability [illegible] NATO

Industry

- Made-to-measure and [illegible] personalized manufacturing [illegible] based sales with [illegible]

Both

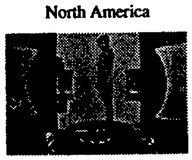
- Increased precision, quality and performance in human systems from apparel to vehicles
- Reduced design and production times and reduced cost.

3D Scanners Used

Europe

VITRONIC whole-body scanner

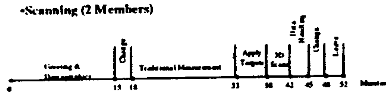
North America



Cyberware WB4 whole-body scanner

CAESAR Process: 3 Stations & 5 Team Members

- Demographics (1 Member)
- Traditional Measurement (2 Members)
- Scanning (2 Members)

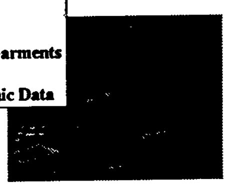


Non-measurement subject time: 25 minutes

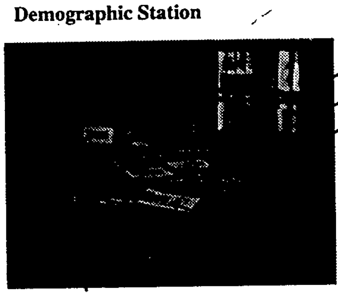
3D Digitizer Rate: 0.5 Megabytes/second
Process Rate: 7.7 Kilobytes/second (1.5%)

Demographic Station

- Scheduling
- Greet Subjects
- Paper Forms
- Select Scanning Garments
- Initiate Floppy
- Enter Demographic Data

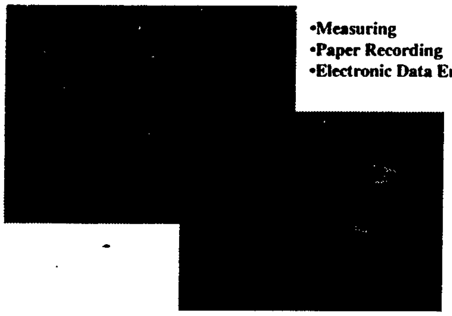


Demographic Station



Team Member (Bridget)
At Demographics Data Entry

Traditional Measurement Station



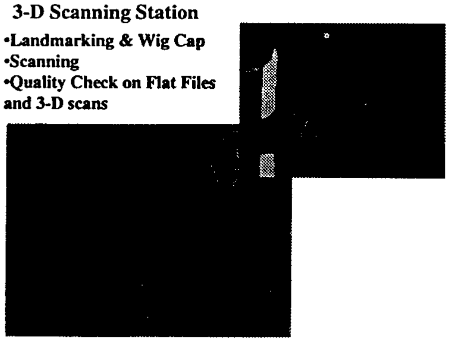
- Measuring
- Paper Recording
- Electronic Data Entry

TRADITIONAL MEASUREMENT LIST

WEIGHT	ANKLE CIRC.
STATURE	FOOT LENGTH
SUBSCAPULAR SKINFOLD	THUMB TIP REACH
TRICEPS SKINFOLD	SITTING HEIGHT
ARM LENGTH (SPINE-SHOULDER)	EYE HT. SITTING
ARM LENGTH (SPINE-ELBOW)	ACROMIAL HT., SITTING
ARM LENGTH (SPINE-WRIST)	ELBOW HT., SITTING (RT)
ARMSCYE CIRC.	KNEE HT. SITTING
CHEST GIRTH (AT SCYE)	THIGH CIRC. MAXIMUM SITTING
BUST/CHEST CIRC.	NECK BASE CIRC.
BUST/CHEST CIRC. UNDER BUST	HEAD CIRC.
WAIST CIRC., PREFERRED	HEAD LENGTH
HIP CIRC., MAXIMUM	BIZYGOMATIC BREADTH
HIP CIRC., MAXIMUM HEIGHT	HEAD BREADTH
WAIST HEIGHT, PREFERRED (RT)	SHOULDER (BIDELTOID) BREADTH
CROTCH HEIGHT	HIP BREADTH SITTING
WAIST FRONT LENGTH	BUTTOCK-KNEE LENGTH
TOTAL CROTCH LENGTH	FACE LENGTH
VERTICAL TRUNK CIRC.	HAND LENGTH
THIGH CIRC. MAXIMUM	HAND CIRC.

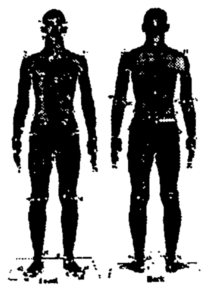
3-D Scanning Station

- Landmarking & Wig Cap
- Scanning
- Quality Check on Flat Files and 3-D scans



Anatomical Landmarks

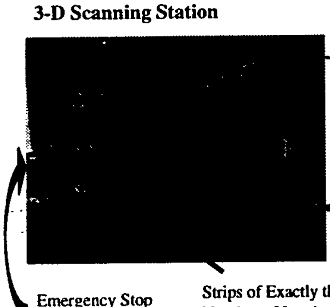
- Landmarks are visible in the color file of the 3D scan
- Software is used to extract landmarks location in 3D



ANATOMICAL LANDMARKS

SELLION	TROCHANTERION (L,R)
INFRAORBITALE (L,R)	HUMERAL EPICONDYLE, MED. (L,R)
TRAGION (L,R)	HUMERAL EPICONDYLE, LAT. (L,R)
GONION (L,R)	OLECRANON (L,R)
SUPRAMENTON	RADIALE (L,R)
NUCHALE	ULNAR STYLOID (L,R)
ACROMION (L,R)	RADIAL STYLOID (L,R)
AXILLA POINT, ANT. (L,R)	METACARPAL-PHALANGEAL II (L,R)
AXILLA POINT, POST. (L,R)	METACARPAL-PHALANGEAL V (L,R)
CLAVICALE (L,R)	DACTYLION (L,R)
SUPRASTERNALE	KNEE CREASE
SUBSTERNALE	FEMORAL EPICONDYLE, MED. (L,R)
THELION/BUSTPOINT (L,R)	FEMORAL EPICONDYLE, LAT. (L,R)
TENTH RIB (L,R)	CALCANEOUS, POST. (L,R)
ILIAC SPINES, ANT. SUP. (L,R)	MALLEOLUS, MED. (L,R)
CERVICALE	SPHYRION (L,R)
TENTH RIB MIDSPINE	MALLEOLUS, LAT. (L,R)
WAIST PREFERRED, POST.	METATARSAL-PHALANGEAL I (L,R)
ILIOCRISTALE	METATARSAL-PHALANGEAL V (L,R)
ILIAC SPINES, POST. SUP. (L,R)	DIGIT II (L,R)

3-D Scanning Station



Scan 3 Postures

Digitized Body Data		Raw Scan Data (Megabytes)
One Scan		8.0
3 Postures Per Subject		24.0
9,000 Subjects		216000
Number of CDs required		332
Cost Per Megabyte	$	27.78
Cost Per Subject ($6 million total)	$	666.83

CAESAR: What is he and what is he not?

- IS 3D in 3 states (postures)
- IS 1D for about 100 measurements (40 traditional and 60 extracted)
- IS 3D for 73 landmarks
- IS demographic
- IS NOT fit data NOR regions of fit.
- IS huge, complex, and can be difficult!

Cleopatra:

A Database Management for CAESAR

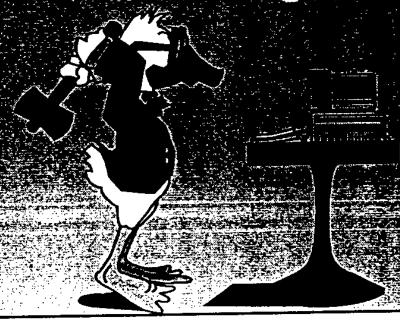
Eric Paquet and Marc Rioux
National Research Council, Canada

International Training Workshop on
Using Anthropometry for Effective Solutions

27-31 March 2000 Kuching, Sarawak, Malaysia

Project Goals

- Finding what you are looking for
- Finding what you are looking for
- Finding what you are looking for



Objective of CAESAR

[illegible]

- Demographic data
- Traditional Anthropometry
- 3D-scanning

Objectives of Cleopatra

- Integrated text and shape search engine
- Search of similar body shapes can be constrained by demographic and/or traditional anthropometric data
- The search engine can also manage 3D clothing files as well as 3D equipment and products
- Graphical icons and visual interface similar to a web search engine
- 3D [illegible] using a web navigator and a VRML viewer plug-in
- [illegible] software

Reference Frame

The reference frame is obtained by computing the principal axis of the tensor of inertia.

The tensor of inertia is defined as:

$$I = [I_{qr}] = \left[\frac{1}{n}\sum_{i=1}^{n}\left[S_i\,(q_i - q_{CM})\,(r_i - r_{CM})\right]\right]$$

Where S_i is the surface of a triangular face, CM is the centre of mass of the object and q and r are equal to x, y and z.

Reference Frame

The principal axes correspond to the eigen vectors of the tensor of inertia:

$$\left[I\mathbf{a}_i = \lambda_i \mathbf{a}_i\right]_{i=1,2,3}$$

It can be shown that the normalised principal axes are translation, scale and rotation invariant. The axes are identified by their corresponding eigen values. The eigen vectors are labelled A, B and C in ascending order of the corresponding eigen values. The tensor of inertia has a mirror symmetry problem that can be solved by computing the statistical distribution of the mass around each principal axis.

Scale

A description of the mass distribution inside the box can be obtained from the corresponding eigen values.

Normal Vectors

A first description of the shape can be obtained from the distribution of the normal vectors. The angles between the normal vectors and the first two principal axes are defined as:

$$\alpha_q = \cos^{-1}\left(\frac{\mathbf{n}\cdot\mathbf{a}_q}{\|\mathbf{n}\|\,\|\mathbf{a}_q\|}\right)$$

Where

$$\mathbf{n} = \frac{[(\mathbf{r}_2 - \mathbf{r}_1)\times(\mathbf{r}_3 - \mathbf{r}_1)]}{\|(\mathbf{r}_2 - \mathbf{r}_1)\times(\mathbf{r}_3 - \mathbf{r}_1)\|}$$

In order to describe the normal vectors we use three histograms called histogram of the first, second and third kind depending on the complexity of the description.

Cords

A cord is defined as a vector that goes from the centre of mass of the model to the centre of mass of a given triangle. The cord is not a unit vector since it has a length. As opposed to a normal, a cord can be considered as a regional characteristic.

Wavelets

The set of wavelet coefficients represents a tremendous amount of information. In order to reduce it, we compute the logarithm of the coefficients in order to enhance the coefficients corresponding to small details, which usually have small amplitudes. Then we integrate the signal for each scale. A histogram representing the distribution of the signal at different scales is then constructed.

Color

[illegible] dimensions: x, y, z, HLS and [illegible]

- The model is first binarized.
- The six-dimensional wavelet transform is then computed.
- The array is transformed sequentially on the first dimension, then on the second dimension and so on.
- The logarithm of the wavelet coefficient is computed and the total signal at each level of resolution is integrated.
- The statistical distribution of the signal among the scales is presented under the form of a histogram.

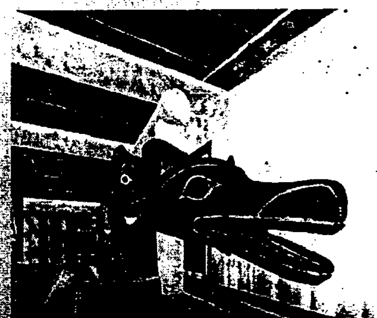
Classification

The classification is made separately for the scale, shape and colour.

Then the global rank is determined as follows:

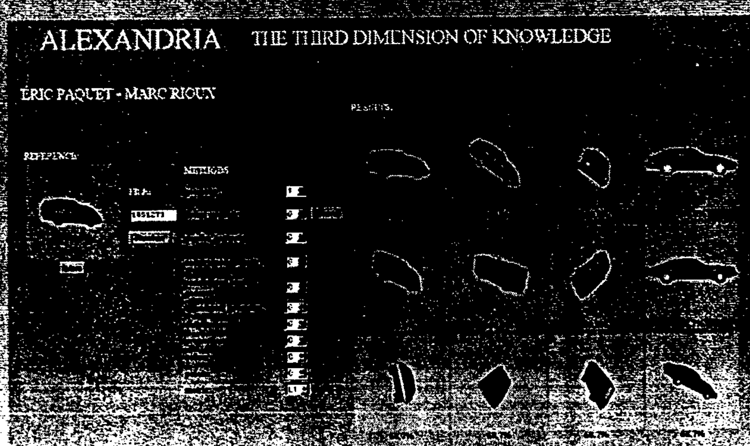
$$rank_{global} = \frac{w_{scale}\, rank_{scale} + w_{shape}\, rank_{shape} + w_{color}\, rank_{color}}{\left(w_{scale} + w_{shape} + w_{color}\right)}$$

Applications

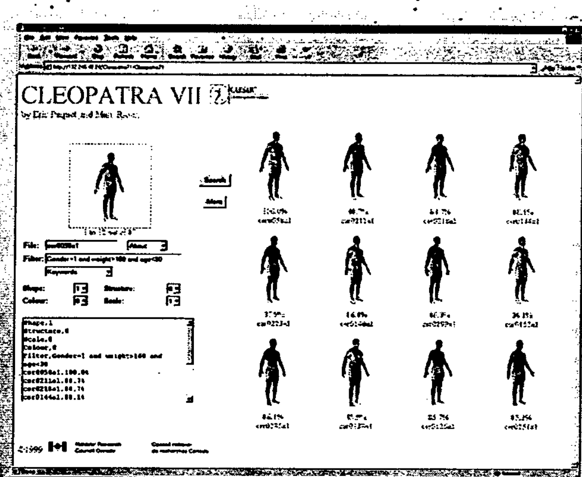


- Part replacement and machining
- Electronic commerce
- Biomedical and anthropometric databases

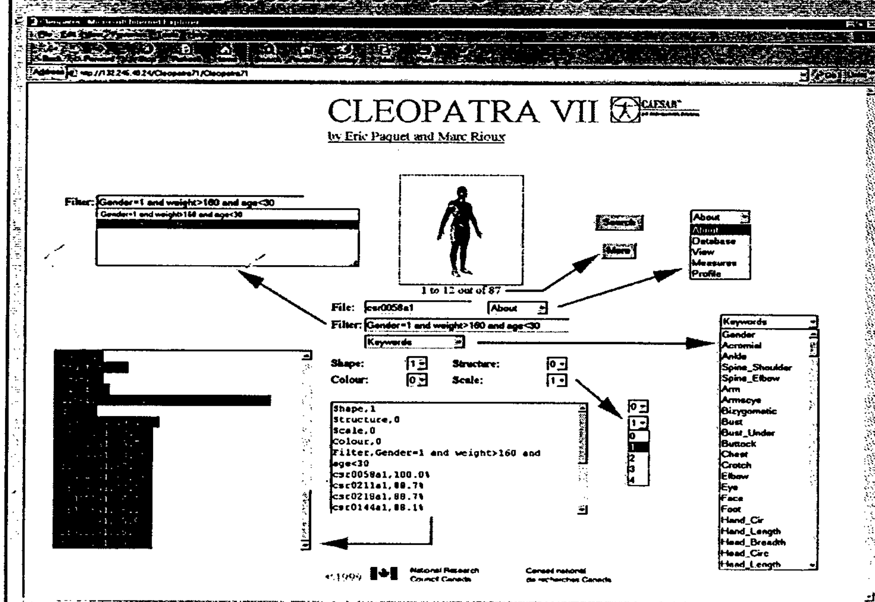
Object Classification: Alexandria

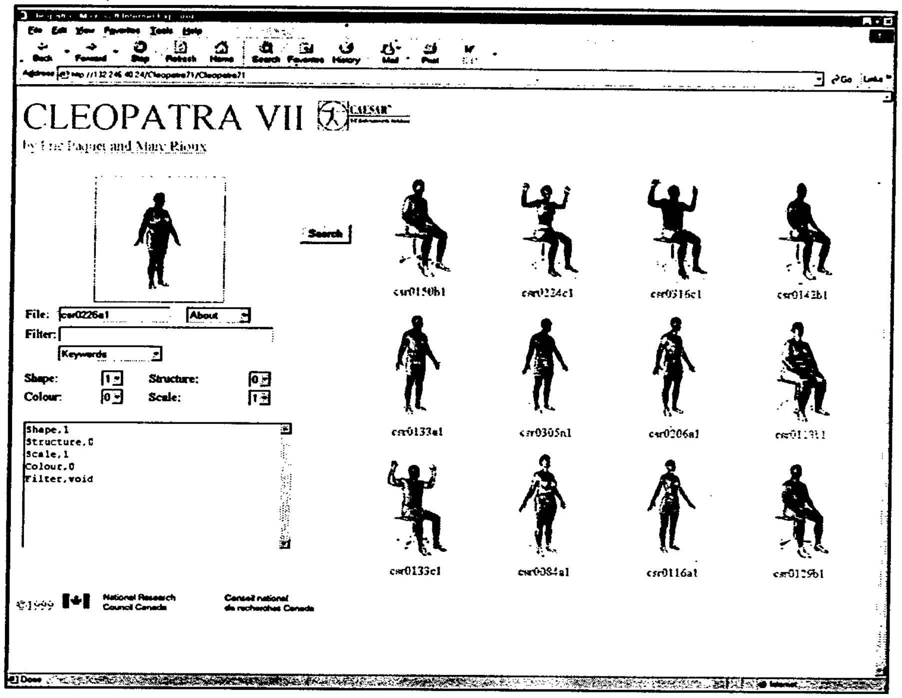


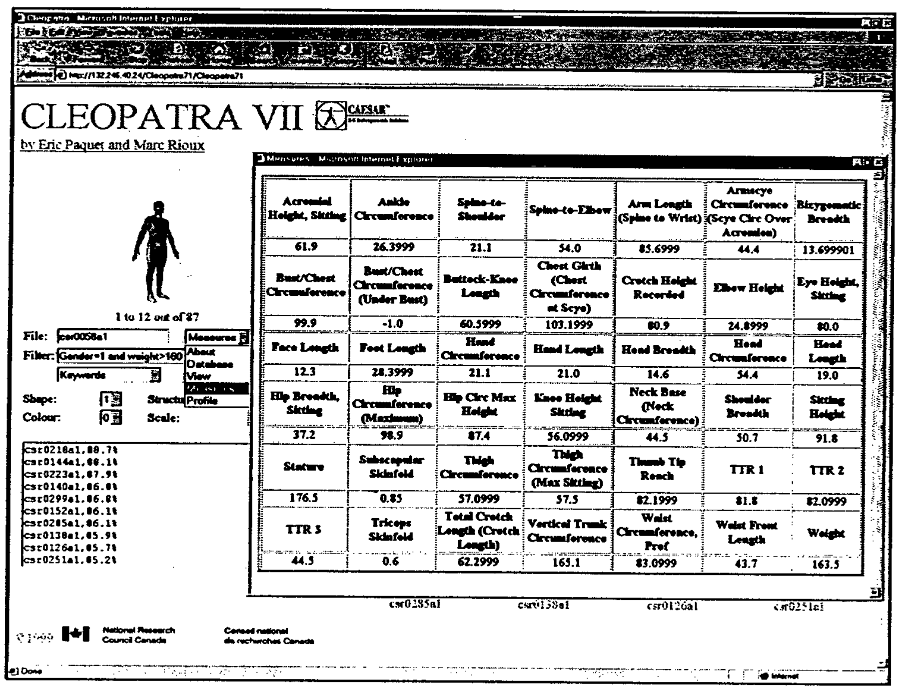
Human Classification: Cleopatra



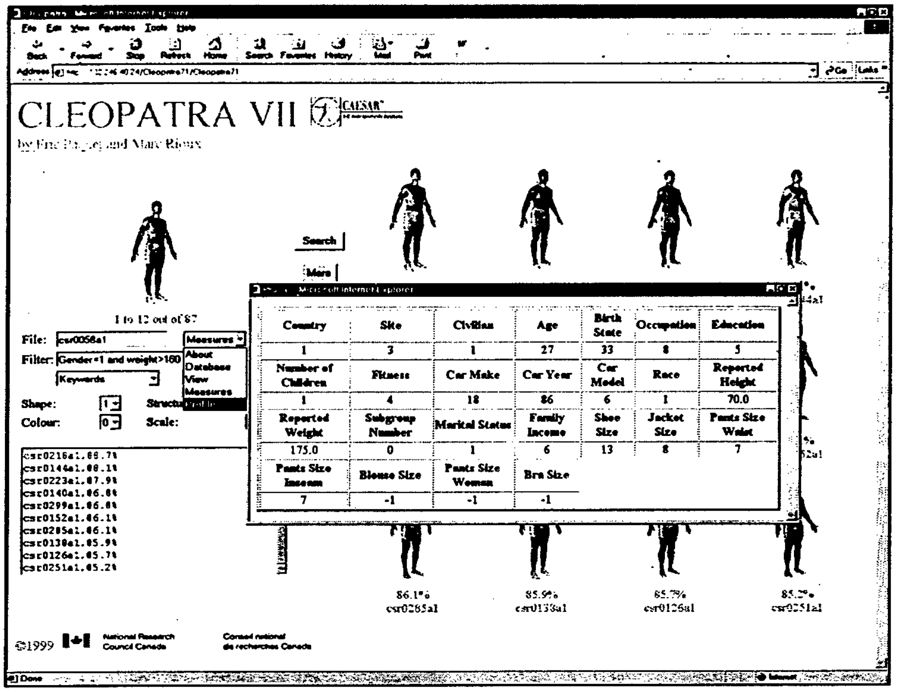
Details of the Interface

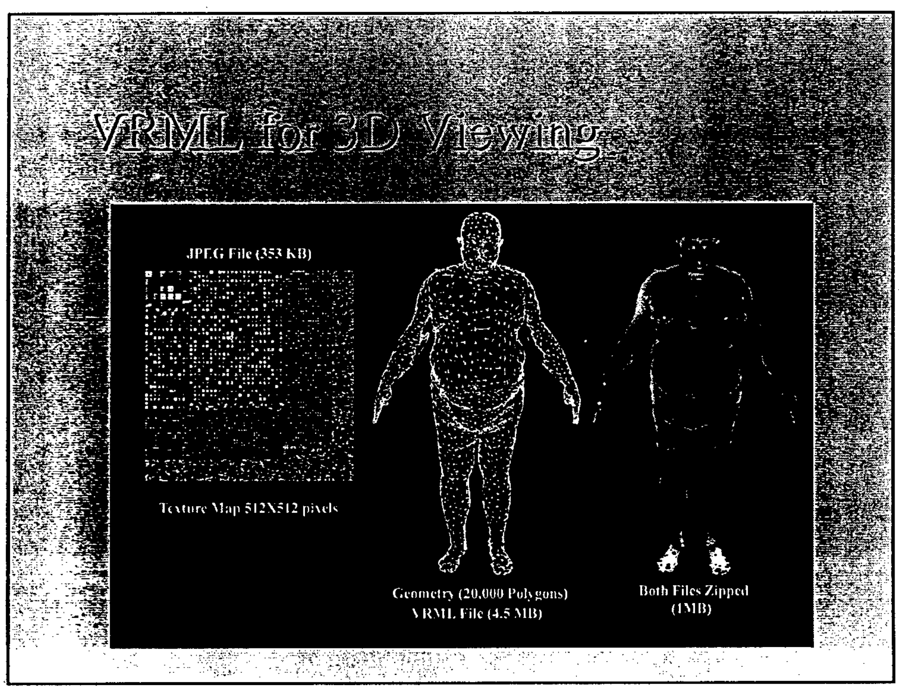


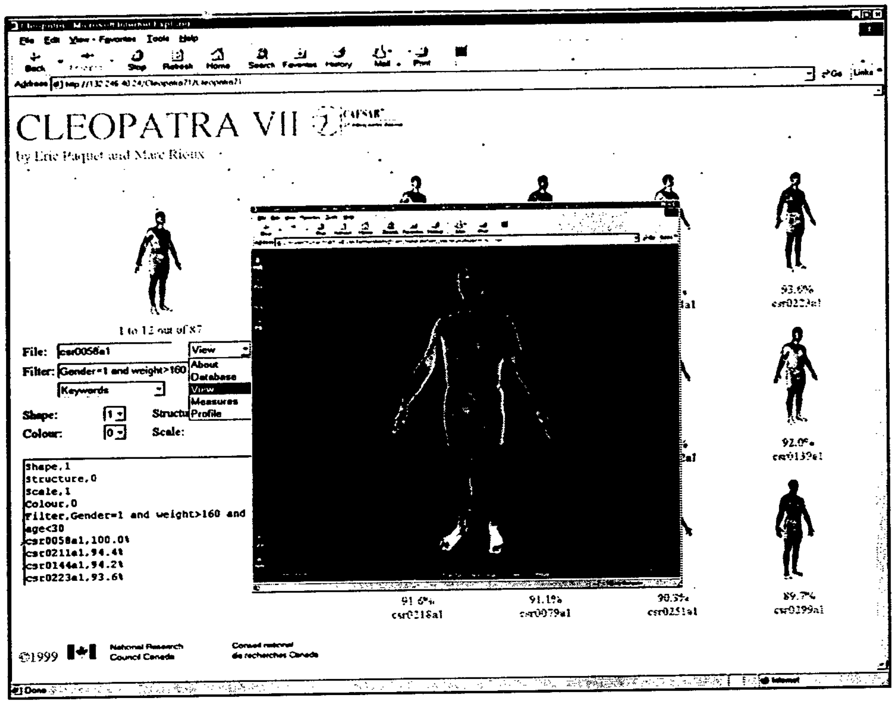


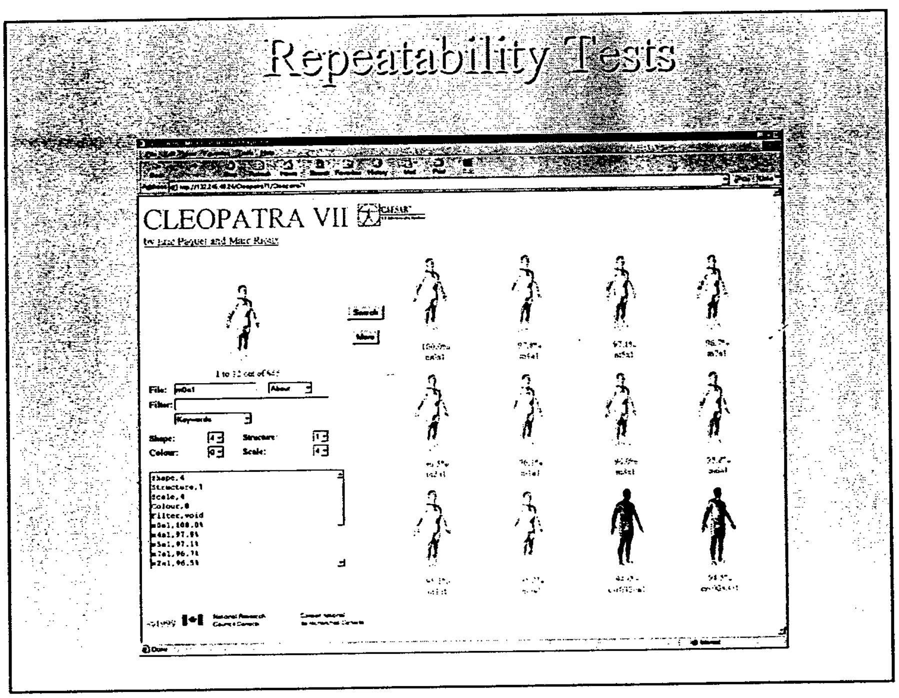


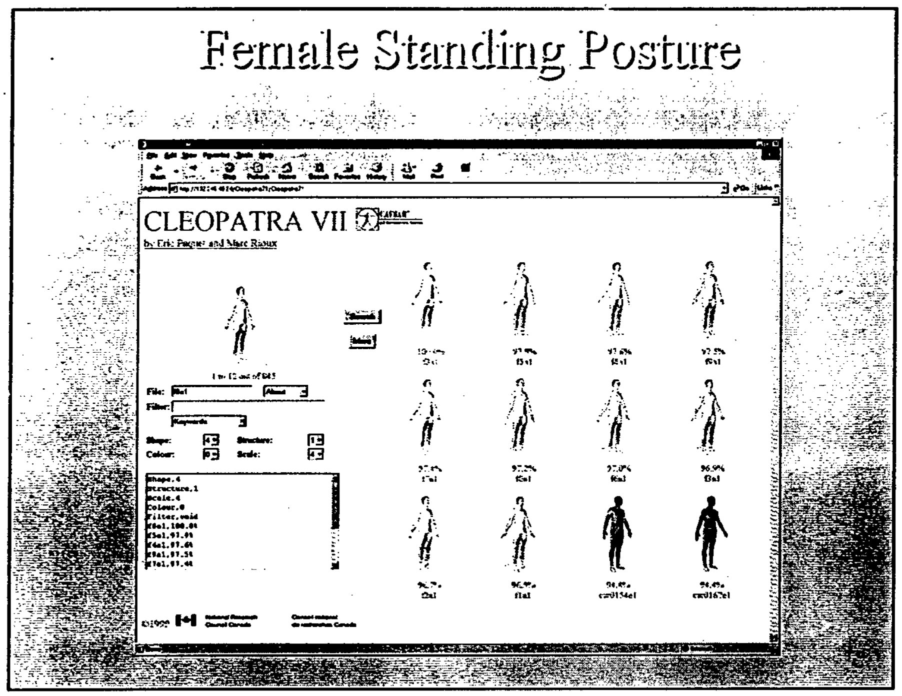
Acromial Height, Sitting	Ankle Circumference	Spine-to-Shoulder	Spine-to-Elbow	Arm Length (Spine to Wrist)	Armscye Circumference (Scye Circ Over Acromion)	Bizygomatic Breadth
61.9	26.3999	21.1	54.0	85.6999	44.4	13.699901
Bust/Chest Circumference	Bust/Chest Circumference (Under Bust)	Buttock-Knee Length	Chest Girth (Chest Circumference at Scye)	Crotch Height Recorded	Elbow Height	Eye Height, Sitting
99.9	-1.0	60.5999	103.1999	80.9	24.8999	80.0
Face Length	Foot Length	Hand Circumference	Hand Length	Head Breadth	Head Circumference	Head Length
12.3	28.3999	21.1	21.0	14.6	54.4	19.0
Hip Breadth, Sitting	Hip Circumference (Maximum)	Hip Circ Max Height	Knee Height Sitting	Neck Base (Neck Circumference)	Shoulder Breadth	Sitting Height
37.2	98.9	87.4	56.0999	44.5	50.7	91.8
Stature	Subscapular Skinfold	Thigh Circumference	Thigh Circumference (Max Sitting)	Thumb Tip Reach	TTR 1	TTR 2
176.5	0.85	57.0999	57.5	82.1999	81.8	82.0999
TTR 3	Triceps Skinfold	Total Crotch Length (Crotch Length)	Vertical Trunk Circumference	Waist Circumference, Pref	Waist Front Length	Weight
44.5	0.6	62.2999	165.1	83.0999	43.7	163.5

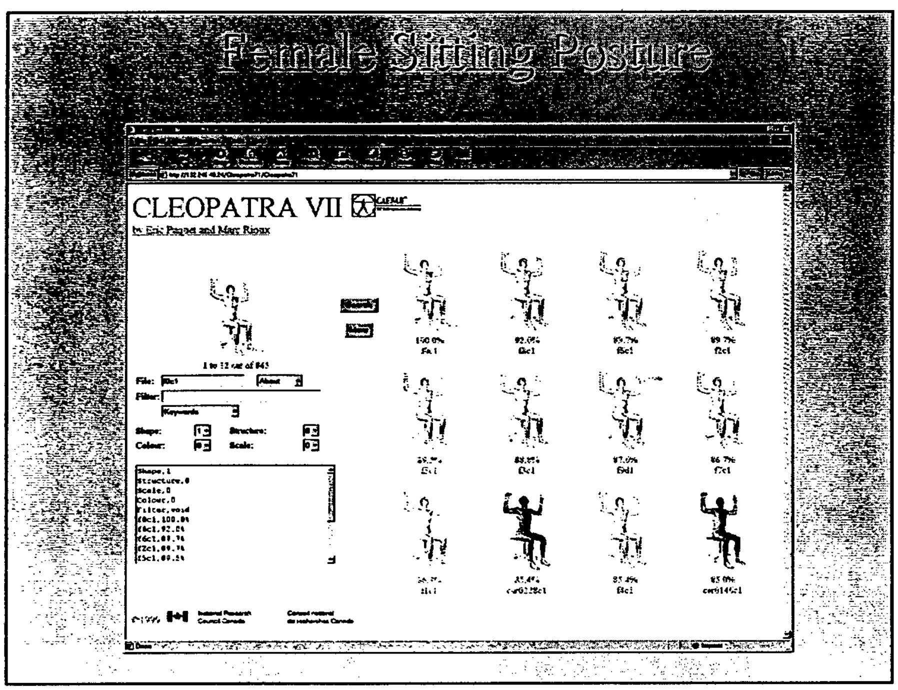

CLEOPATRA VII
CAESAR
Search
More
1 to 12 out of 87
File: csr0056a1
Filter: Gender=1 and weight>160
Keywords
Measures
About
Database
View
Measures
Shape:
Colour:
Scale:
csr0216a1.88.7%
csr0144a1.88.1%
csr0223a1.87.9%
csr0140a1.86.8%
csr0299a1.86.8%
csr0152a1.86.1%
csr0285a1.86.1%
csr0138a1.85.9%
csr0126a1.85.7%
csr0251a1.85.2%
Country 1
Site 3
Civilian 1
Age 27
Birth State 33
Occupation 8
Education 5
Number of Children 1
Fitness 4
Car Make 18
Car Year 86
Car Model 6
Race 1
Reported Height 70.0
Reported Weight 175.0
Subgroup Number 0
Marital Status 1
Family Income 6
Shoe Size 13
Jacket Size 8
Pants Size Waist 7
Pants Size Inseam 7
Blouse Size -1
Pants Size Women -1
Bra Size -1
©1999
National Research Council Canada
Conseil national de recherches Canada

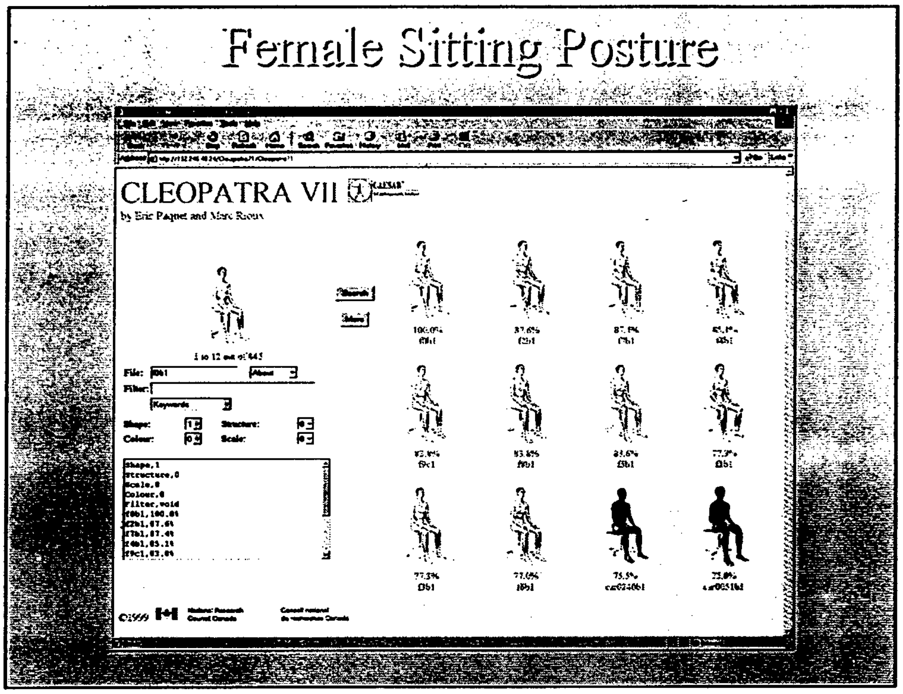

VRML for 3D Viewing
JPEG File (353 KB)
Texture Map 512X512 pixels
Geometry (20,000 Polygons)
VRML File (4.5 MB)
Both Files Zipped
(1MB)

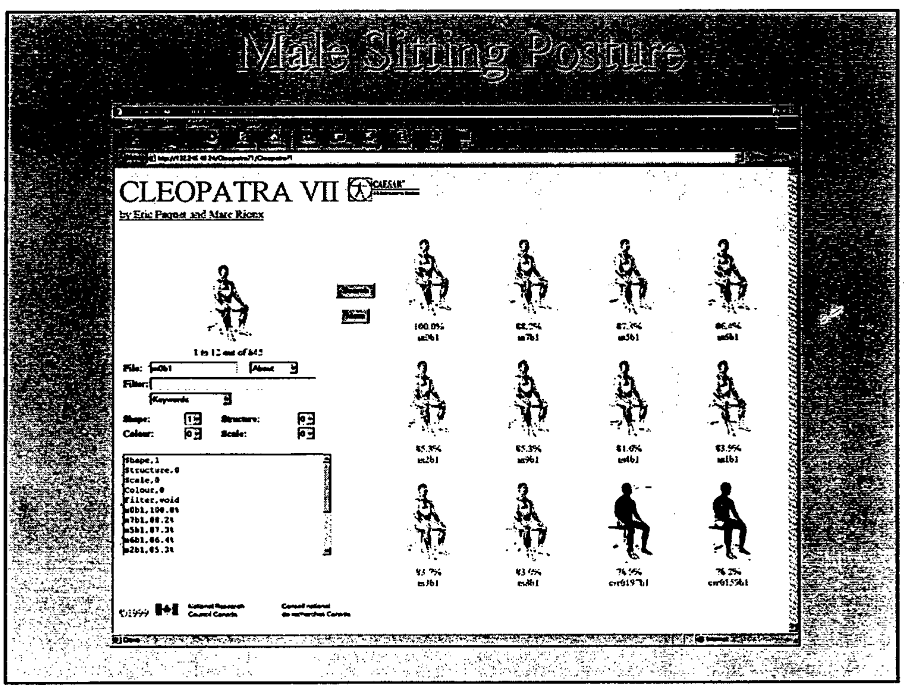

CLEOPATRA VII
by Eric Paquet and Marc Rioux
1 to 12 out of 87
File: csr0058a1
Filter: Gender=1 and weight>160
Keywords
Shape:
Colour:
Scale:
View
About
Database
Measures
Profile
Shape,1
Structure,0
Scale,1
Colour,0
Filter,Gender=1 and weight>160 and age<30
csr0058a1,100.0%
csr0211a1,94.4%
csr0144a1,94.2%
csr0223a1,93.6%
93.6% csr0223a1
92.0% csr0139a1
91.6% csr0218a1
91.1% csr0079a1
90.5% csr0251a1
89.7% csr0299a1
©1999
National Research Council Canada
Conseil national de recherches Canada

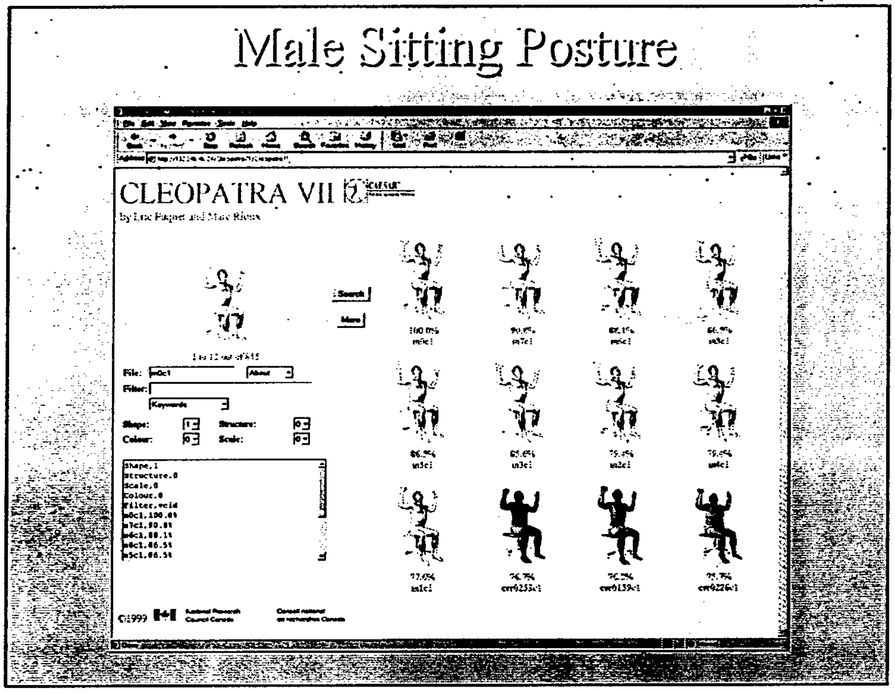

Repeatability Tests
CLEOPATRA VII

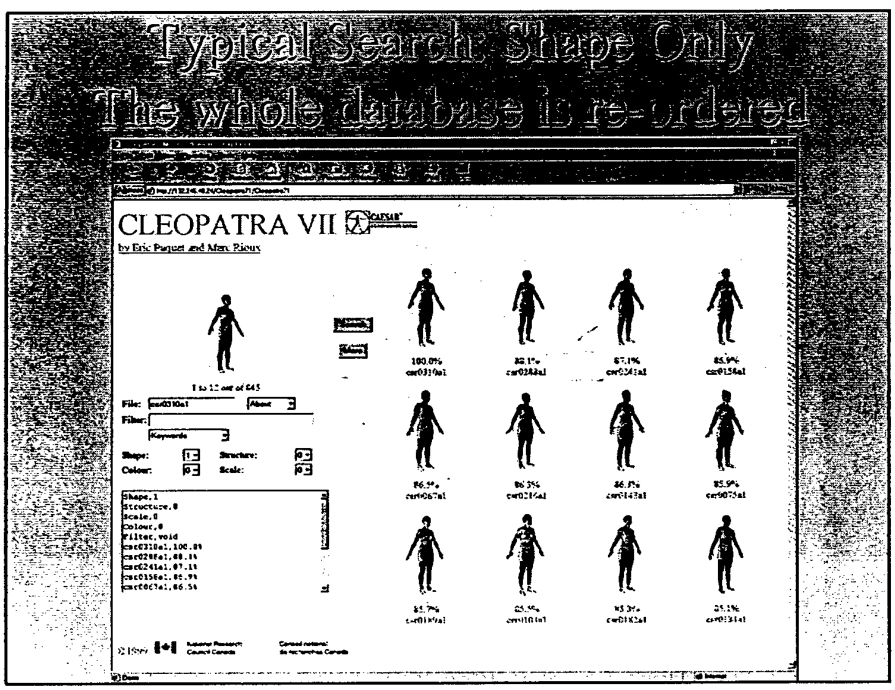

Female Standing Posture
CLEOPATRA VII
by Eric Paquet and Marc Rioux

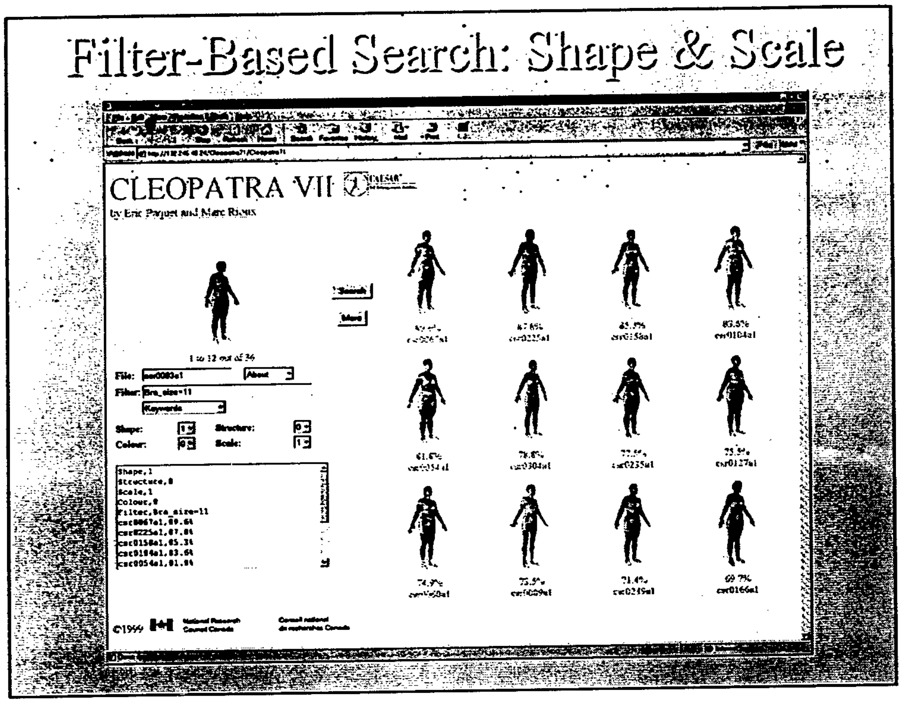

Female Sitting Posture
CLEOPATRA VII
by Eric Paquet and Marc Rioux

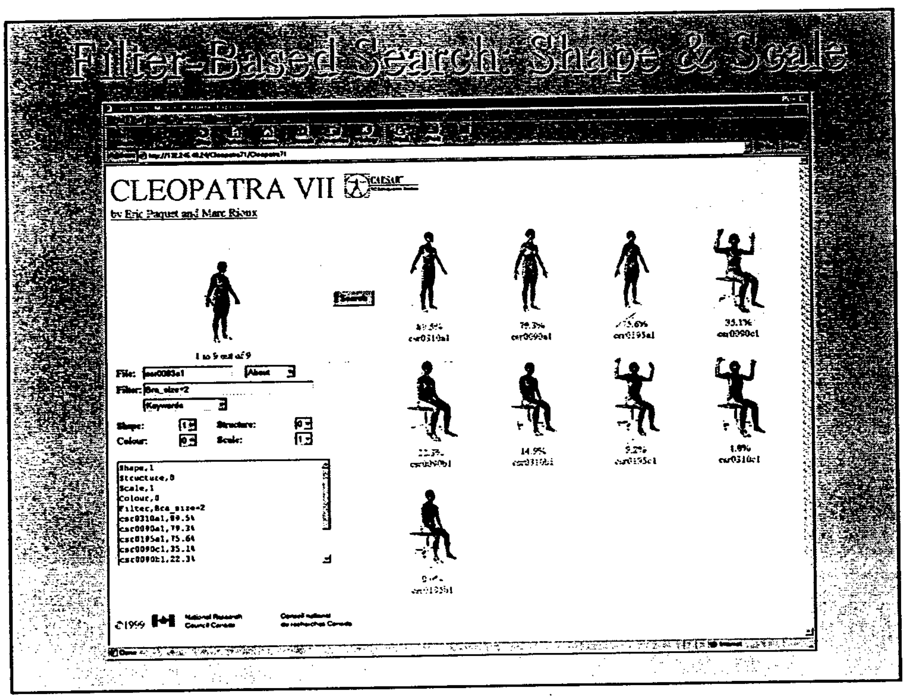

Female Sitting Posture
CLEOPATRA VII
by Eric Paquet and Marc Rioux
©1999

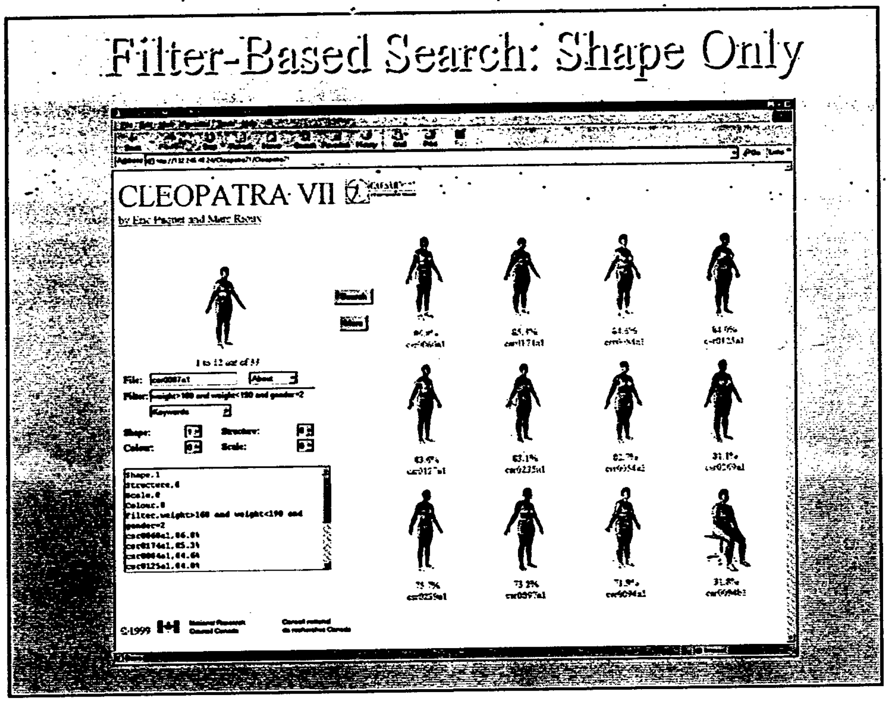

Male Sitting Posture
CLEOPATRA VII
by Eric Paquet and Marc Rioux
©1999

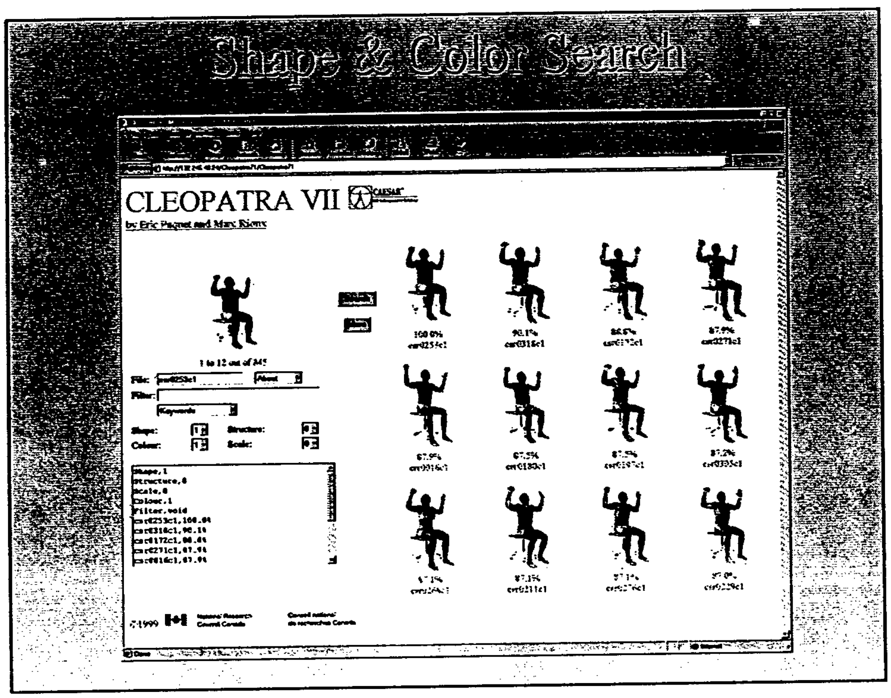

Male Sitting Posture
CLEOPATRA VII
File:
Filter:
Shape:
Structure:
Colour:
Scale:


Typical Search: Shape Only
The whole database is re-ordered
CLEOPATRA VII
by Eric Paquet and Marc Rioux
File:
Filter:
Shape:
Structure:
Colour:
Scale:


Filter-Based Search: Shape & Scale
CLEOPATRA VII
by Eric Paquet and Marc Rioux
Search
More
1 to 12 out of 36
File:
About
Filter:
Keywords
Shape:
Structure:
Colour:
Scale:
©1999
National Research Council Canada
Conseil national de recherches Canada


Filter-Based Search: Shape & Scale
CLEOPATRA VII
by Eric Paquet and Marc Rioux
Search
1 to 9 out of 9
File:
About
Filter:
Keywords
Shape:
Structure:
Colour:
Scale:
©1999
National Research Council Canada
Conseil national de recherches Canada


Filter-Based Search: Shape Only
CLEOPATRA VII


Shape & Color Search
CLEOPATRA VII

Cleopatra Server: On-line Search

- New NT Server, Dual Xeon 550 MHz
- 2X36 GB Hard Drives with RAID
- Oracle 8i + Oracle Apps Server
- Zipped VRML files (1 MB)
- Three sites available on-line
- Multiple databases with pass words
- Influence of pose study

Summary

- Full Database Search
- Visual Interface
- Compact 3D Descriptors (250 Bytes)
- Interface with Analysis Software
- Research Prototype On-Line:
  http://132.246.40.24/Caesar1/Cleopatra71.html
  User name and password at: Marc.Rioux@nrc.ca

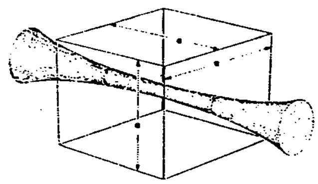
References

- E. Paquet and M. Rioux, "Content-based Access of VRML Libraries", IAPR International Workshop on Multimedia Information Analysis and Retrieval, *Lecture Notes in Computer Sciences*, Springer 1464, Hong Kong, China, 20-32 (1998).

- E. Paquet and M. Rioux, "A Content-based Search Engine for CAD and VRML Databases", Dedicated Conference on Robotics, Motion and Machine Vision in the Automotive Industries, *Proc. ISATA 31*, 427-434, Düsseldorf, Germany (1998).

- E. Paquet and M. Rioux, "Crawling, Indexing and Retrieval of Three-dimensional Data on the Web in the Framework of MPEG-7", Third International Conference On Visual Information Systems- Visual'99, June 2-4, Amsterdam, The Netherlands, 179-186 (1999).

Gaussian Beam Propagation



Volume of View

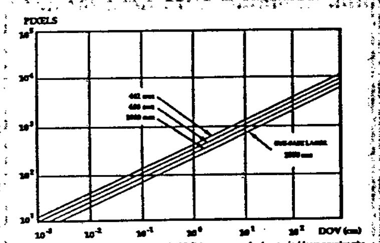
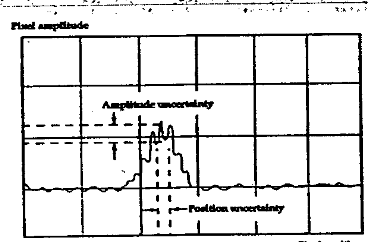


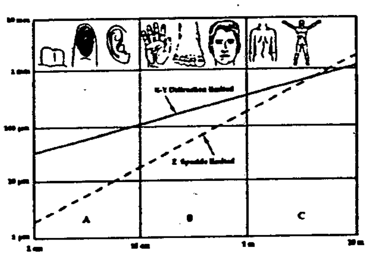
Image resolution of a diffraction-limited optical 3-D laser scanner for four typical laser wavelengths.

Optical Limits (Speckle)



Speckle noise limits the position sensing resolution.

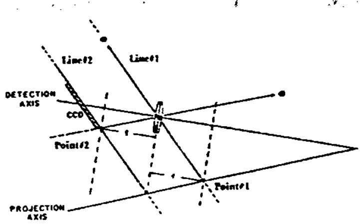
Optical Limits (Resolution)



Optical Limits (Typical Examples)

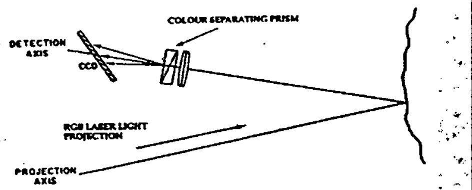
Scanner type	A	B	C
Resolution (µm) (X,Y,Z)	50,50,5	250,250,50	2000,2000,400
Numerical resolution (LSB, 2 bytes)	1	10	30
Volume of view (cm)	6.5	65	195
File size (MB) 1024x1024x2bytes	2	2	2

Optical Limits (Scheimpflug)



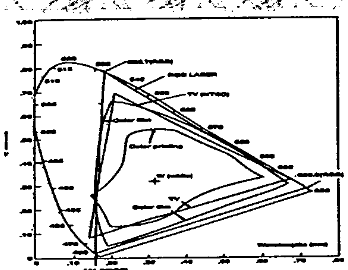
The geometric construction of the Scheimpflug condition.

Color 3D Digitizing (Registered)

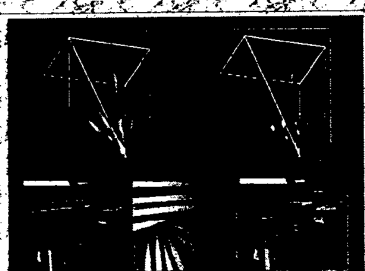


Geometry for simultaneous recording of shapes and colours.

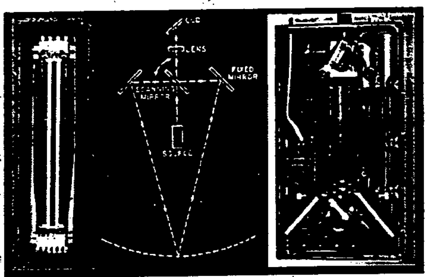
Color 3D Digitizing (Laser Sources)



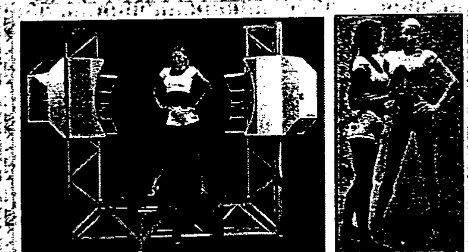
Color 3D Digitizing (Modeling)



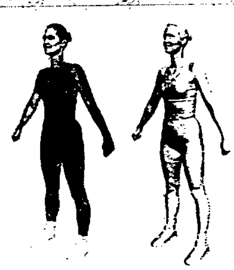
Optical Triangulation



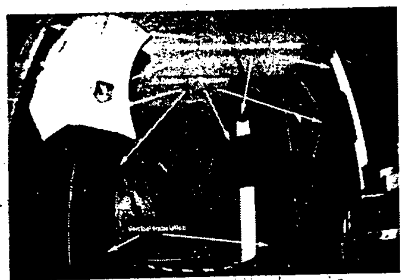
3D Body Scanners (Cyberware)



3D Body Scanners (Cyberware)



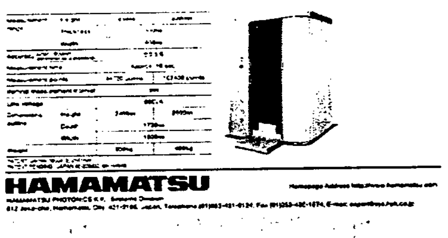
3D Body Scanners (Cyberware)



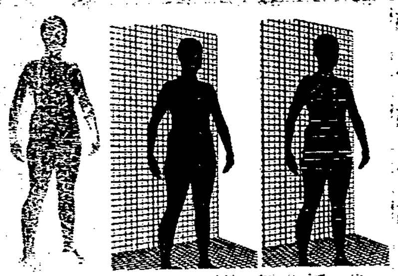
3D Body Scanners (Cyberware)

3D Body Scanners (Vitronics)

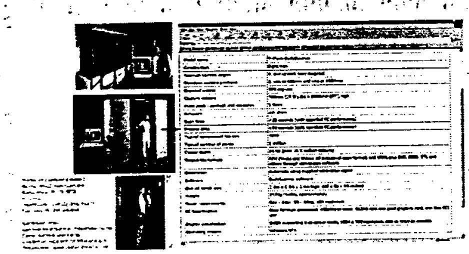
3D Body Scanners (Hamamatsu)

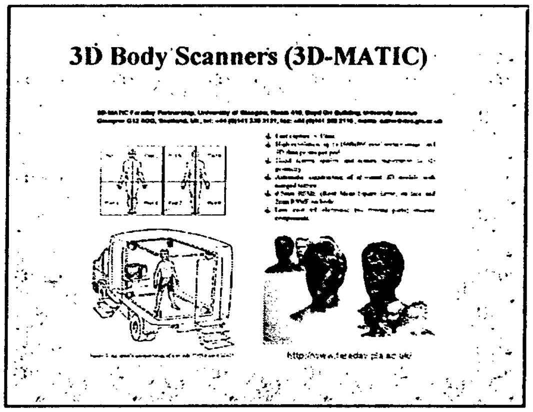


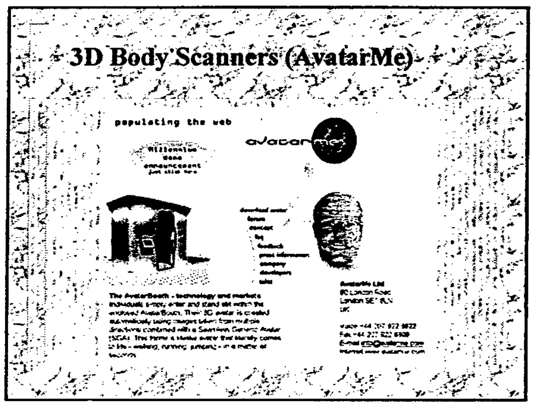
3D Body Scanners (Hamamatsu)

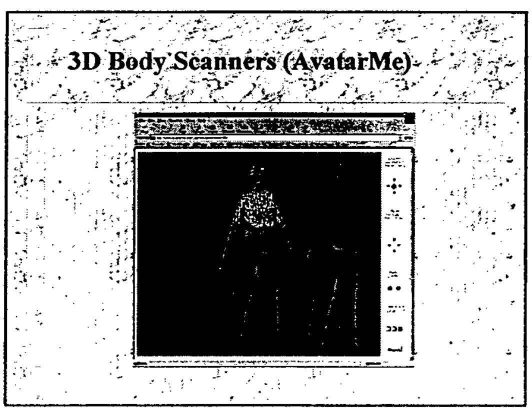


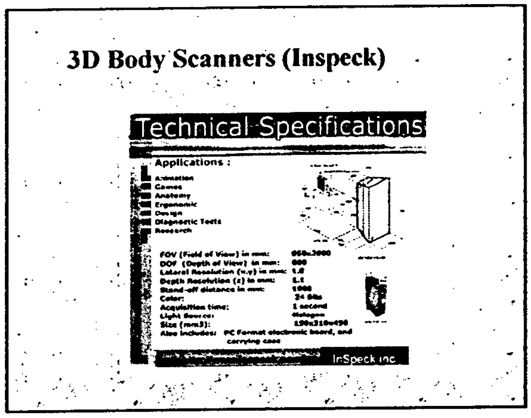
3D Body Scanners (W&W)

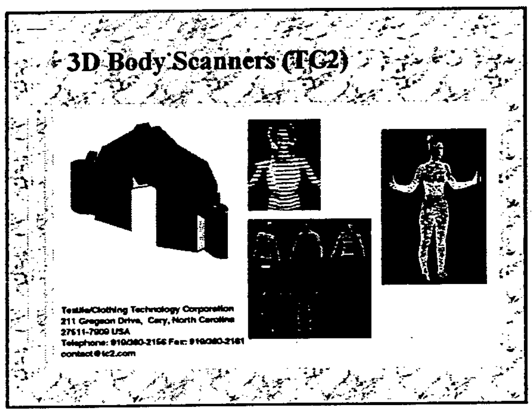


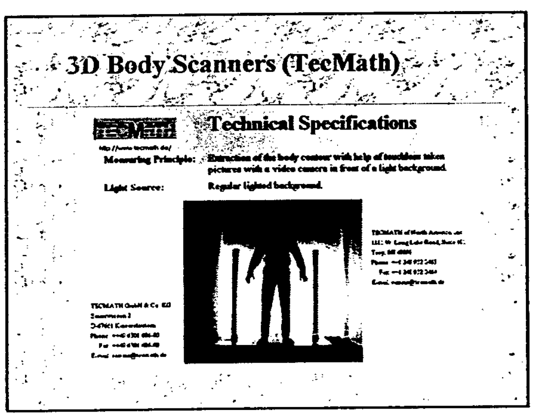

3D Body Scanners (3D-MATIC)
http://www.faraday.gla.ac.uk/


3D Body Scanners (AvatarMe)
populating the web


3D Body Scanners (AvatarMe)


3D Body Scanners (Inspeck)
Technical Specifications
Applications :
Animation
Games
Anatomy
Ergonomic
Design
Diagnostic Tests
Research
FOV (Field of View) in mm:
DOF (Depth of View) in mm:
Lateral Resolution (x,y) in mm:
Depth Resolution (z) in mm:
Stand-off distance in mm:
Color: 24 bits
Acquisition time: 1 second
Light Source: Halogen
Size (mm3):
Also includes: PC Format electronic board, and carrying case
InSpeck inc


3D Body Scanners (TC2)
Textile/Clothing Technology Corporation
211 Gregson Drive, Cary, North Carolina
contact@tc2.com


3D Body Scanners (TecMath)
Technical Specifications
Measuring Principle: Extraction of the body contour with help of touchless taken pictures with a video camera in front of a light background.
Light Source: Regular lighted background.

3D Body Scanners (TecMath)

TECMATH

Technical Specifications

Measuring Principle:	Extraction of the body contour with help of touchless taken pictures with a video camera in front of a light background.
Light Source:	Regular lighted background.
Measuring Configuration:	Measuring of the front and side part in different postures.
Measurement Cabin:	Width x Depth x Height = 1.5m x 4m x 2.2 m
Computer System:	Pentium PC, 100 MHz
Calibration:	Calibration with help of a reference object inside the measuring plane.
Measurement Time:	Several camera pictures of the person in different postures. Data interpretation is independent from measurement.
Measure Extraction:	Model-based calculation of th body dimensions with an adaptation of the human model RAMSIS.
Measurement Precision:	Approximately 1 cm concerning the body height.

References

- Rioux, M. Digital 3-D imaging: theory and applications. SPIE Proceedings, Videometrics III, International Symposium on Photonic and Sensors and Controls for Commercial Applications. Boston, MA. October 31 - November 4, 1994. Vol. 2350. pp. 2-15.
- Rioux, M. Color 3-D electronic imaging of the surface of the human body. SPIE Proceedings, Automatic Systems for the Identification and Inspection of Humans, San Diego, CA. July 28-29, 1994. Vol. 2277. pp. 42-54.
- Jones, P.R.M. and Rioux, M. Three-dimensional surface anthropometry: applications to the human body. Optics and Lasers in Engineering, 28: 89-117; 1997

PolyWorks

International Training Workshop on

Using

Anthropometry for Effective Solutions

27-31 March 2000 Kuching, Sarawak

MALAYSIA

Instructor: Marc Rioux

National Research Council Canada

PolyWorks Modules

- **IMAlign** — IMAlign precisely aligns sets of 3D scans in order to bring all measured 3D data into a unique coordinate system.
- **IMMerge** — IMMerge is an automated program that computes high-resolution polygonal models from sets of aligned 3D scans.
- **IMEdit** — IMEdit provides a comprehensive set of advanced editing tools allowing you to customize your polygonal models for all your applications.
- **IMCompress** — IMCompress is a powerful surface-based algorithm that automatically removes redundant information from large 3D polygonal models.
- **IMTexture** — IMTexture is a module for color 3D digitizers that automatically generates texture maps for color models reduced with IMCompress.
- **IMView** — IMView is an entirely configurable 3D viewer for visualizing 3D polygonal models.

PolyWorks Modules

IMAlign

Set of six 3D scans acquired from different viewpoints and their alignment (center)

The alignment accuracy

PolyWorks Modules

IMAlign

IMAlign's Rapid Inspection Module (RIM)

CAD Model

8 Scans aligned to the CAD model

PolyWorks Modules

IMAlign

IMMerge

IMEdit

IMCompress

IMTexture

IMView

Aligning Multiple 3D Datasets

48,243,961 aligned points

PolyWorks Modules

IMAlign

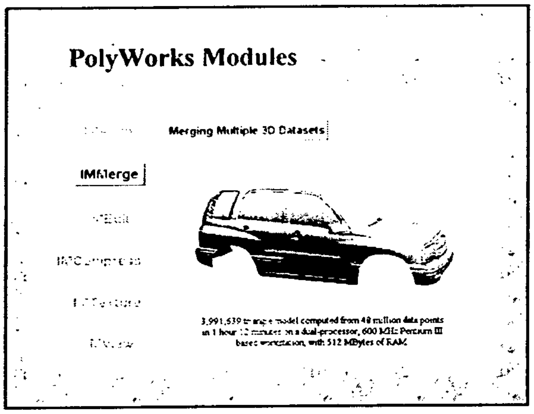
IMMerge

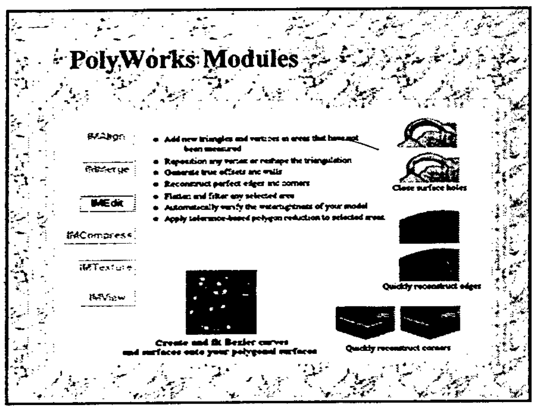
IMEdit

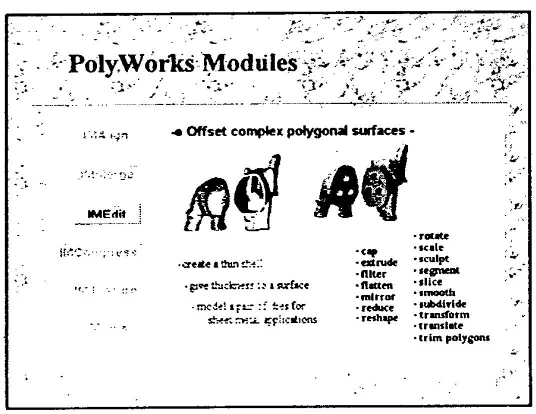
IMCompress

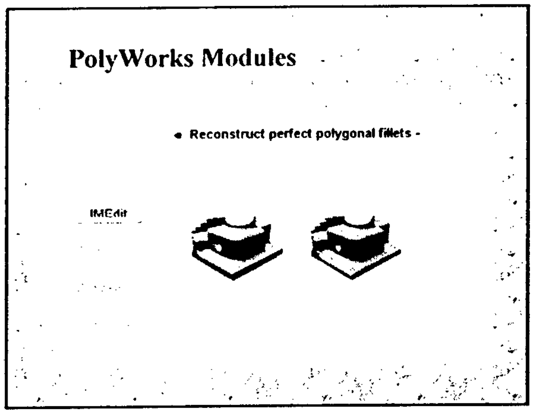
24 precisely aligned 3D scans ready for merging

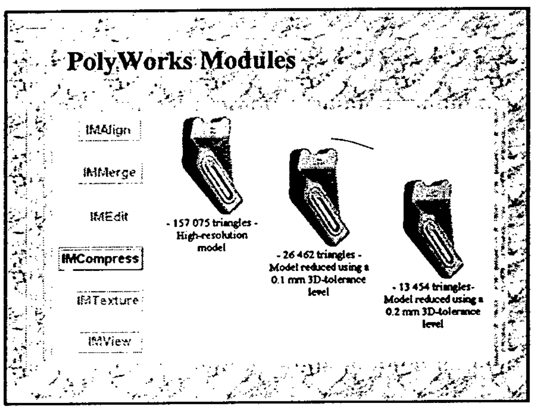
24 meshes merged into a high-precision surface triangulation

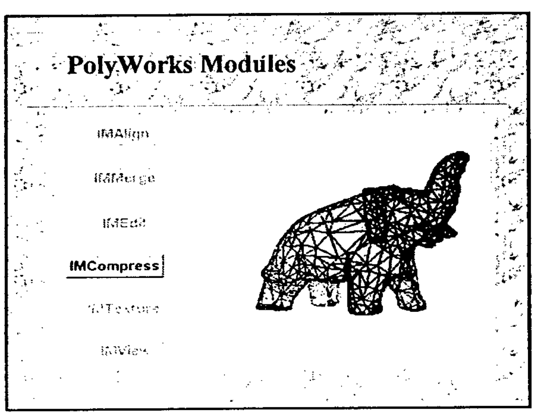

PolyWorks Modules
Merging Multiple 3D Datasets
IMMerge
3,991,539 triangle model computed from 48 million data points
in 1 hour 12 minutes on a dual-processor, 600 MHz Pentium III
based workstation, with 512 MBytes of RAM.


PolyWorks Modules
IMAlign
IMMerge
IMEdit
IMCompress
IMTexture
IMView
Add new triangles and vertices in areas that have not been measured
Reposition any vertex or reshape the triangulation
Generate true offsets and walls
Reconstruct perfect edges and corners
Flatten and filter any selected area
Automatically verify the watertightness of your model
Apply tolerance-based polygon reduction to selected areas
Close surface holes
Quickly reconstruct edges
Create and fit Bezier curves
and surfaces onto your polygonal surfaces
Quickly reconstruct corners

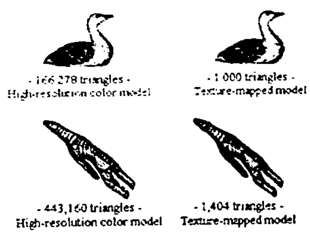

PolyWorks Modules
IMEdit
Offset complex polygonal surfaces
create a thin shell
give thickness to a surface
model a pair of dies for
sheet metal applications
cap
extrude
filter
flatten
mirror
reduce
reshape
rotate
scale
sculpt
segment
slice
smooth
subdivide
transform
translate
trim polygons


PolyWorks Modules
• Reconstruct perfect polygonal fillets -
IMEdit


PolyWorks Modules
IMAlign
IMMerge
IMEdit
IMCompress
IMTexture
IMView
- 157 075 triangles -
High-resolution model
- 26 462 triangles -
Model reduced using a 0.1 mm 3D-tolerance level
- 13 454 triangles-
Model reduced using a 0.2 mm 3D-tolerance level

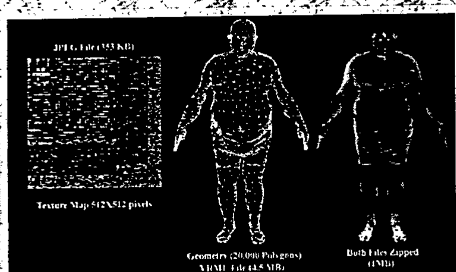

PolyWorks Modules
IMAlign
IMMerge
IMEdit
IMCompress

PolyWorks Modules

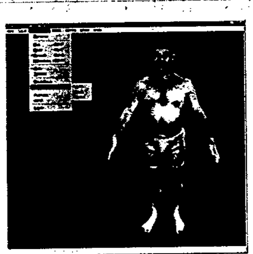


IMTexture

PolyWorks Modules



PolyWorks Modules



IMView

PolyWorks Modules

PolyWorks/Inspector Version 2.0

- Global point-to-CAD comparisons
- Point to CAD comparisons at specific locations
- Point-to-feature comparisons
- Feature-to-feature comparisons

- Maps comparison errors onto CAD surfaces using a color-coded representation
- Includes an advanced color scale editor for better color plots
- Allows the specification of in/out tolerances for pass/fail inspection
- Generates customizable reports in HTML, Word, or Excel formats

PolyWorks, CAESAR & Cleopatra

IMAlign	Register the multiviews body scans
IMMerge	Produce a high definition model (>1 M triangles)
IMEdit	Filling holes and close the model (STL for rapid prototyping)
IMCompress	Use in Cleopatra for compact file size (30,000 triangles)
IMTexture	To handle texture at various level of resolution
IMView	To visualize subject in 3D graphics mode (in color, as a wiremesh, as a solid model)

PolyWorks, CAESAR & Cleopatra

Computer Platforms Supported:

- All Silicon Graphics platforms running IRIX 5.3 and up.
- All Intel-based workstations running Windows NT 4.0.

3D Digitizers Supported:

- Cyberware
- Gom (Atos)
- Inspeck
- Minolta
- Vitana
- Voxelan
- EOIS
- Hymarc
- Kreon
- Steinbichler
- Vitronic
- 3D Scanners

PolyWorks, CAESAR & Cleopatra

Polygonal Format Translators Supported:

- Bidirectional translators
- DWB
- DXF
- Inventor (ASCII and binary)
- OBJ
- OpenFlight 14.2 and 15.2
- POL (InnovMetric's binary format which supports multi-contour polygons and color information)
- STL (ASCII and binary)
- VRML 1.0 and 2.0
- Write-only translators
- IGES 106 (polylines), 108, 126 and 128

PolyWorks, CAESAR & Cleopatra

Users of PolyWorks:

AMG, Germany
Boeing, USA
EDF, France
General Electric, USA
Gifu University, Japan
IFREMER, France
Land Rover, UK
Mainframe Entertainment, Canada
NASA, USA
Naval Surface Warfare Center, USA
NHK, Japan
Padova University, Italy
Procter & Gamble, USA
Rolls Royce, UK
Telenor, Norway
Venture Industries, USA
Volvo, Sweden
BMW, Germany
Daimler Benz, Germany
Ford, USA
GH-Paderborn University, Germany
Hitachi, Japan
IREQ / Hydro-Québec, Canada
Lockheed Martin, USA
Mattel, USA
National Institutes of Health, USA
Naval Research Laboratory, USA
Nortel, Canada
Peugeot, France
Rockwell, USA
Short Brothers, UK
TNO, The Netherlands
Vickers Defence Systems, UK
Waseda University, Japan

Thursday, 30 March 2000

Integrate®
by Kathleen Robinette

Rapid Prototyping Techniques
by Marc Rioux

Survey Process Optimization
by Kathleen Robinette

Hands-on Anthropometric Methods
by Kathleen Robinette

INTEGRATE

Presented at the International Training Workshop on Using Anthropometry for Effective Solutions

Teresa Perkins
Kathleen M. Robinette*

Sytronics Inc.
Dayton OH

*Air Force Research Laboratory
Human Interface Technology Branch
2255 H Street
Wright-Patterson AFB OH 45433-7022
Phone: (937) 255-8810
Fax: (937) 255-8752
e-mail: kath.robinette@wpafb.af.mil

Advanced Engineering Technology Applications Sytronics, Inc.

Overview

» Background

» Functions and Capabilities

- Single-Object Operations
- Multi-Object Operations
- General Operations

Advanced Engineering Technology Applications Sytronics, Inc.

Background

» What is INTEGRATE?

- A software tool developed by Sytronics, Inc. (Dennis Burnsides) for the CARD Laboratory in 1994 to visualize, analyze, and manipulate 3-D scanned data

» Why INTEGRATE?

- Existing software packages did not provide the capabilities or unique functions necessary for CARD tasks

Advanced Engineering Technology Applications Sytronics, Inc.

Background

»INTEGRATE was developed as a prototype

- fairly basic user interface
- provides unique functions

»INTEGRATE is free!

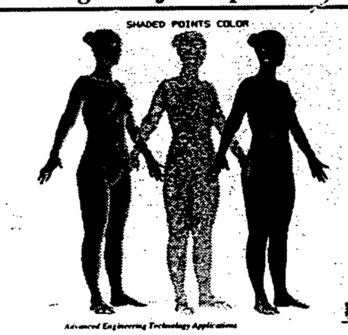
http://www.hec.afrl.af.mil/cardlab/

Single-Object Operations

»Single-object visualization operations allow presentation of the data in several forms:

- Point Cloud
- Surface (Polygon)
  - Shaded
  - Color
- Wireframe

Single-Object Operations



Wireframe Slide Here

Head Scan

Advanced Engineering Technology Applications Sytronics, Inc.

Single-Object Operations

»Landmarks can be identified:

- Manually through point picking
  - use existing or unmarked points
- Semi-automatically (CAESAR)
  - 73 pre-marked points

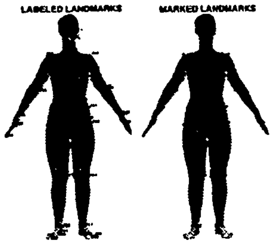
Advanced Engineering Technology Applications Sytronics, Inc.

newlm.tif

Advanced Engineering Technology Applications Sytronics, Inc.

Single-Object Operations

»INTEGRATE can display landmarks as labeled (Z1, Z2, ...) or marked (+)

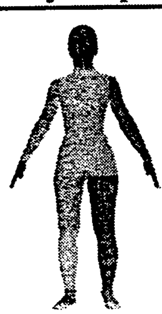


Single-Object Operations

»Segmentation -

- Used to divide a dataset into smaller pieces for simpler analysis of each segment, or a more sophisticated analysis of the entire dataset
- Manual
- Automatic (This feature has not been tested and is not in the free version of INTEGRATE)

Single-Object Operations



Single-Object Operations

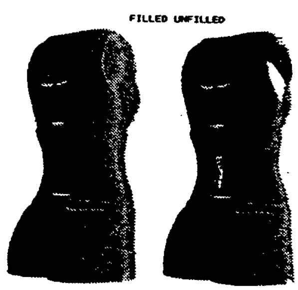
»Scans are filled by interpolation to replace void points caused by:

- extraneous light sources
- missing data due to shading or orientation
- bad surface reflectivity (dark hair)

»Procedure

- segment (needs to be a cylindrical object because filling is based on radius)
- resample each segment
- do fill

Single-Object Operations



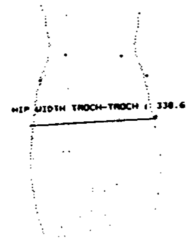
Single-Object Operations

»Measurement Extraction

- Straight line point-to-point distances
- Circumferences
- Contours
- Virtual Calipers
- Surface areas
- Volumes

Single-Object Operations

»Point-to-Point Distance - the distance between two points of interest

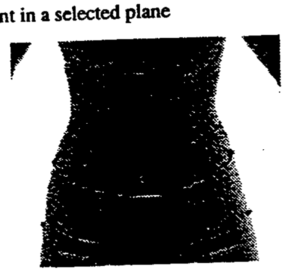


Advanced Engineering Technology Applications

Sytronics, Inc.

Single-Object Operations

»Circumference - the actual distance around a body segment in a selected plane

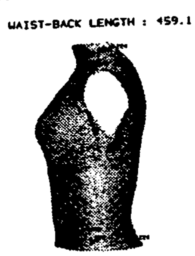


Advanced Engineering Technology Applications

Sytronics, Inc.

Single-Object Operations

»Contour - the surface distance between two points on the surface



Advanced Engineering Technology Applications

Sytronics, Inc.

frontcon.gif angleconcolor.tif

Advanced Engineering Technology Applications

Sytronics, Inc.

Virtual Calipers Slide Here

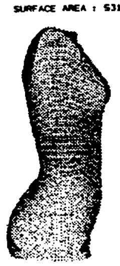
Advanced Engineering Technology Applications

Sytronics, Inc.

Single-Object Operations

»Surface Area and Volume

VOLUME : 20,608,802 MM3
SURFACE AREA : 531,184 MM2



Advanced Engineering Technology Applications

Sytronics, Inc.

Multi-Object Operations

✓Multi-object manipulation

- Landmark and surface-based (visual) registration for multiple objects

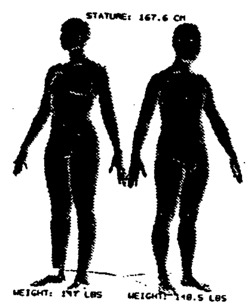
Multi-object visualization

- Transparent surfaces allow the operator to view the exact relationship between two or more surfaces
  - •Fit Visualization

Advanced Engineering Technology Applications

Sytronics, Inc.

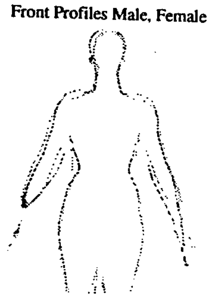
Multi-Object Operations



Sytronics, Inc.

Multi-Object Operations

Front Profiles Male, Female

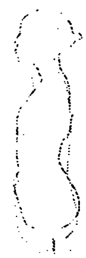


Advanced Engineering Technology Applications

Sytronics, Inc.

Multi-Object Operations

Side Profiles Male, Female



Advanced Engineering Technology Applications

Sytronics, Inc.

Multi-Object Operations

Multi-object manipulation
- Landmark and surface-based registration for multiple objects

✓Multi-object visualization
- Transparent surfaces allow the operator to view the exact relationship between two or more surfaces
  - •Fit Visualization

Advanced Engineering Technology Applications

Sytronics, Inc.

Fit of Flight Suit
Slide Here

Advanced Engineering Technology Applications

Sytronics, Inc.

Radial Difference Mapping (RDM)

- »Two scans are aligned
  - Surface matching technique (4 landmarks: Cervicale, Suprasternale, and Clavicale (left, right))
  - Visual Inspection
- »Filled by interpolation
- »Placed in a common coordinate system
- »Distances calculated between surfaces along each radius value
- »RESULT: Regions of differences (e.g., 10 mm) shown as a Radial Difference Map (RDM)

Multi-Object Operations

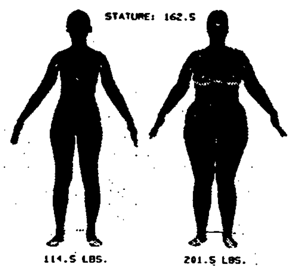
DISTANCE	COLOR
< 10 mm	Green
10 - 20 mm	Orange
20 - 30 mm	Grey
30 - 40 mm	Purple
40 - 50 mm	Blue
> 50 mm	Black
Negative	Yellow

3rdmfront.gif

Multi-Object Operations

3rdmback.gif

Multi-Object Operations



Multi-Object Operations

DISTANCE	COLOR
Negative	Pink
< 20 mm	Light Blue
20 - 40 mm	Green
40 - 60 mm	Slate
60 - 80 mm	Gray
80 - 100 mm	Orange
> 100 mm	Light Green

Rdmfront.gif

Rdmback.gif

Rdm45.gif

General Operations

» Comprehensive audit trail which records all user actions
  - allows end users to make an independent judgement about the validity of modified data
  - troubleshooting for software errors or operator errors
  - create script files which can automatically reproduce one or more sessions exactly

» Batch file capability
  - scripts can be parameterized to automatically extract new information from hundreds of datasets

General Operations

»Color-coded objects

»User has direct control of objects and object features

»"Active Object" feature

»Displays information about the active object, overall mode of the system, and a summary of the state of current objects

Summary

»INTEGRATE is a software tool

- view or look at cases
- extract new information from cases
- visualize and quantify differences between individual subjects in the cases

»CAESAR = 3-D data

»INTEGRATE = Measure in 3-D and map fit in 3-D

References

1. Burnsides, D.B., *Software for Visualization, Analysis, and Manipulation of Laser Scan Images, 1997.*

National Research Council Canada
Conseil national de recherches Canada

Institute for Information Technology
Visual Information Technology Group

RAPID PROTOTYPING TECHNIQUES

P. Boulanger, M. Rioux
VIT Lab, National Research Council Canada
Ottawa, Canada, K1A 0R6
http://www.vit.iit.nrc.ca

International Training Workshop on
Using Anthropometry for Effective Solutions
27-31 March 2000 Kuching, Sarawak, Malaysia

Canada

NRC · CNRC

Why use Rapid Product Development?

There are many business pressures on industry today affecting new products:

- A demand for reduced lead times
- Increased product variety and quality requirements
- Worldwide competition
- Short product life cycles
- Smaller product runs and customized products
- Just-in-time manufacturing

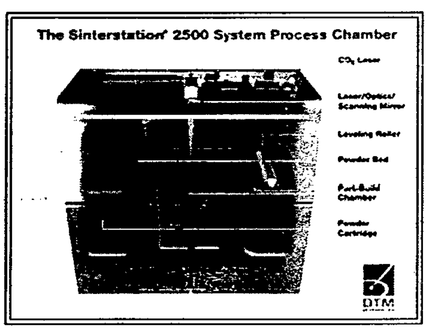
NRC · CNRC

Enabling Technologies for RPD

- Computer Aided Engineering (CAE)
- Rapid Prototyping Machines
- Conversion Technologies
- Reverse Engineering
- Dimensional Validation
- 3-D Measuring Devices
- Virtual Display Systems
- Production Simulation Tools
- Advanced Materials

NRC · CNRC

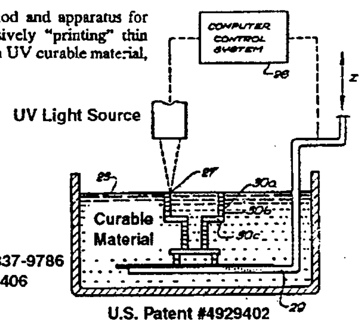
Rapid Prototyping Machines
(Laser Sintering)



NRC · CNRC

Rapid Prototyping Machines
(Stereolithography)

"Stereolithography" is a method and apparatus for making solid objects by successively "printing" thin layers of a curable material, e.g., a UV curable material, one on top of the other.



3D Systems
26081 Avenue Hall
Valencia, CA 91355
U.S. Toll Free Number: (888) 337-9786
U.S. FAX Number: (661) 294-8406
moreinfo@3dsystems.com

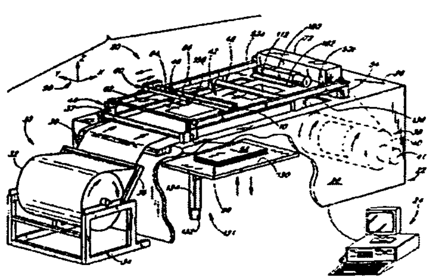
U.S. Patent #4929402

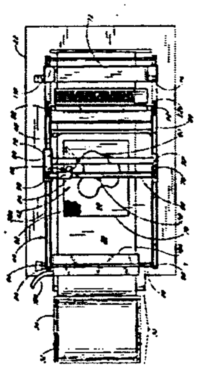
NRC · CNRC

Rapid Prototyping Machines
(Laminated Object Manufacturing)

HELISYS

Helisys, Inc.
24015 Garnier Street
Torrance, California 90505-5319
U.S.A.
Tel: (310) 891-0600
Fax: (310) 891-0626

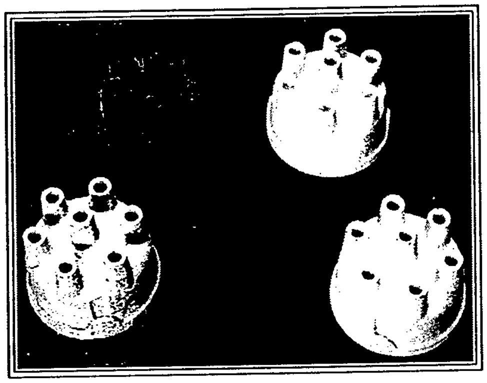




US Patent # 5730817

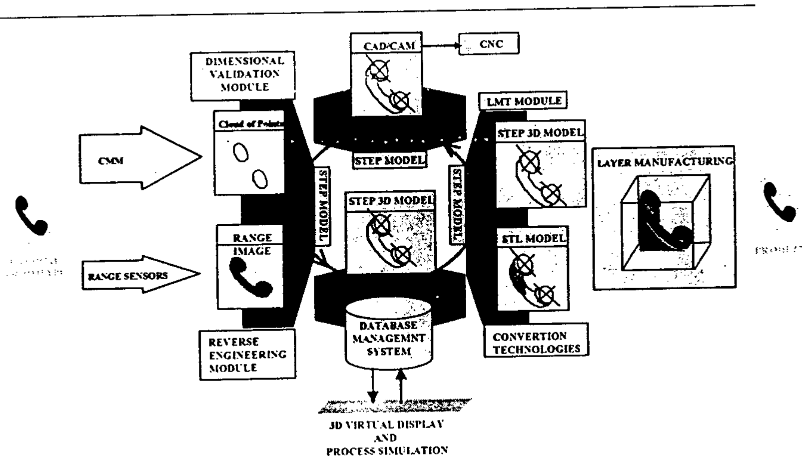
NRC · CNRC

Rapid Prototyping Machines
(Samples)



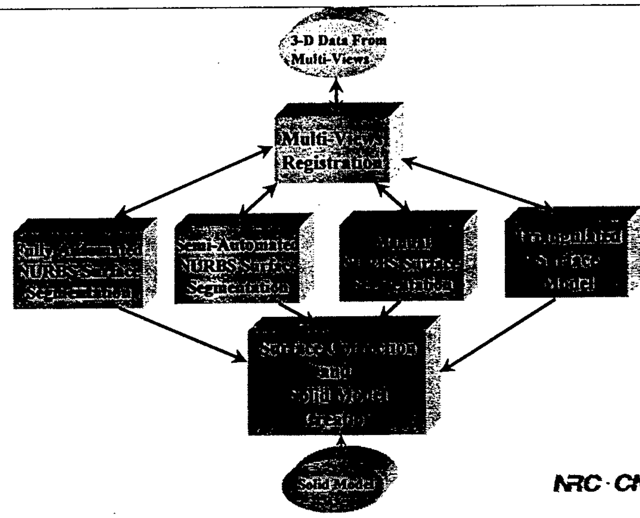
NRC · CNRC

Toward an Integrated RPD Environment



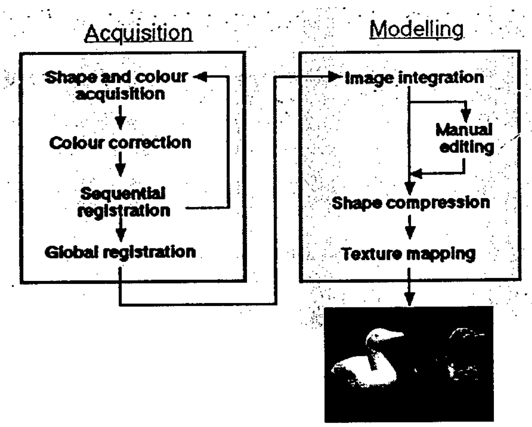
NRC · CNRC

What is Reverse Engineering?



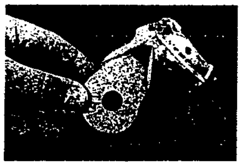
NRC · CNRC

Reverse Engineering Based on Triangular Meshes (Basic Principles)



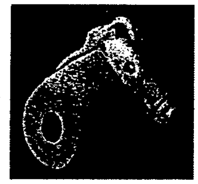
NRC · CNRC

Production of a Hand-Made Toy in Two Weeks

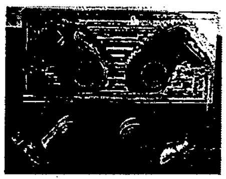


Hand-Made Toy

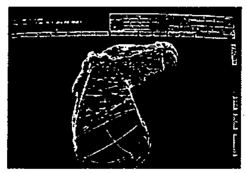
Multi-View Registration



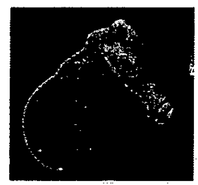
View Integration



Production Mould



Interface to CAD

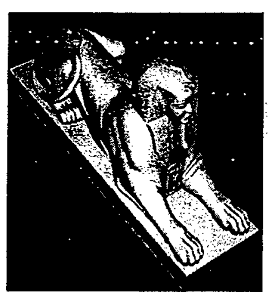


Solid Model Creation

NRC · CNRC

Direct Replica of Large Museum Objects

3-D Scan of the Sculpture



STL model

Replicas produced
by a 3-D Laser Sintering
Machine (Kaiplast Inc.)

NRC · CNRC

Reverse Engineering Based on Triangular Meshes (Conclusion)

- The most practical and economical way to do reverse engineering today
- Model construction is fully automated and produces results that are useful for direct replication and integration in CAD as a base for design
- It is also a way to integrate all the data known about an object into a non-redundant representation
- Does not produce real CAD representation as defined today by current CAD systems

NRC · CNRC

Commercial Solution to Triangulated Surface Modeling (InnovMetric)

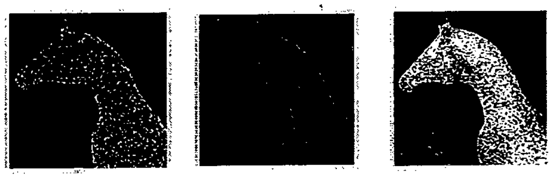
Polyworks is a triangular model creation suite capable of the following functions:

•High-precision 3-D scan alignment for measuring any surface area of an object
•Merging aligned 3-D scans into accurate high-resolution triangulated models with color mapping capabilities
•Advanced polygon editing optimized for very large models
•Advanced polygon reduction capabilities based on true 3-D tolerances
•The previous results were obtained using this software

NRC · CNRC

Commercial Solution to Triangulated Surface Modeling (GEOMAGIC)

- GEOMAGIC Wrap® is a software designed for automatic surface reconstruction from point cloud data.
- It produce automatically a 3D delaunay triangulation of independent data points.
- Combined with a scanner digitizer, Wrap creates precise digital models from complex 3D objects automatically.



NRC · CNRC

Reverse Engineering Based on NURBS Surface Segmentation (Introduction)

- The number of points produced by these range sensors is usually very large (typically over 100,000 points).

- **There is a need to compress the size of the data set to make it more manageable.**

- **Failure to do so in the past has slowed down the applicability of the technology.**

NRC · CNRC

Reverse Engineering Based on NURBS Surface Segmentation (Introduction)

- Recent commercial attempts to solve this problem are mainly based on manual segmentation.

- Programs such as *Surfacer* from Imageware, *Surface Studio 9.0 from Alias WaveFront*, and *STRIM* from MATRA, are usually very tedious to use and require a skilled operator.

- **There is a need for the automation of the segmentation process in order for the technology to be really practical.**

NRC · CNRC

Reverse Engineering Based on NURBS Surface Segmentation (Design Criteria)

- The segmentation must be robust to the presence of geometrical discontinuities.

- Complex geometrical representations must be statistically justified.

- Smoothness between surface patches is realized using blending functions.

- The data set must be on a connected graph such as a triangulation.

NRC · CNRC

Reverse Engineering Based on NURBS Surface Segmentation (Algorithm I)

- Do an initial partitioning of the data set based on a first order Bézier surface model using a robust fitting technique
- Perform grouping from the initial partition until the approximation tolerance is reached
- Generalize regions into higher order Bézier patches using geometrical heuristics
- Proceed with more groupings until no more regions are generalized

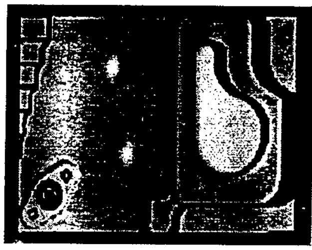
NRC · CNRC

Reverse Engineering Based on NURBS Surface Segmentation (Algorithm II)

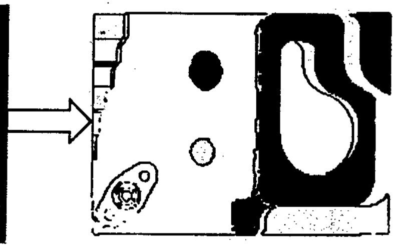
- Approximate the boundary of the region using a 2-D spline in the u-v plane
- Adjust smoothness between surface regions.
- Save the set of trimmed Bézier surfaces extracted into a CAD compatible format such as IGES-144

NRC · CNRC

Reverse Engineering Based on NURBS Surface Segmentation (Results)



Range Image



Segmented Regions

NRC · CNRC

Reverse Engineering Based on NURBS Surface : Commercial Solutions (STRIM)

MATRA DATAVISION

STRIM

- STRIM FOR PROTOTYPING includes an integrated suite of time-saving applications for cutting model production costs.
- This package is the most complete and integrated solution on the market for digitized points editing, surface reconstruction, direct machining on points, and stereolithography file generation.
- Built-in surface checking and healing functions ensure that the exported CAD models are of good quality, significantly reducing model production time.
- Cloud of point segmentation is performed manually.

NRC · CNRC

Reverse Engineering : Commercial Solutions (SURFACER)

CURVE CREATION/MODIFICATION:

Surfacer allows curves to be created manually from measurement data to any tolerance or smoothness that the user specifies. Surfacer's analysis tools ensure that the curve is accurate and continuous.

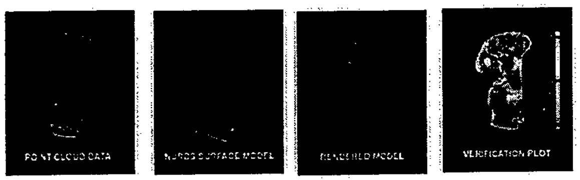
Imageware

SURFACE CREATION/MODIFICATION:

Surfacer possesses a complete set of skin-based modeling tools.

GEOMETRIC ANALYSIS:

Surfacer ensures that the model you created meets your specifications. A surface-to-cloud plot shows you exactly how much your model deviates from the collected data points, while surface continuity plots and virtual tube lights ensure the quality of your surfaced model



NRC · CNRC

Reverse Engineering : Commercial Solutions (SurfaceStudio 9.0)

CURVE CREATION/MODIFICATION:

Surface Studio allows curves to be created manually from measurement data to any tolerance or smoothness that the user specifies. Surface Studio analysis tools ensure that the curve is accurate and continuous.

SURFACE CREATION/MODIFICATION:

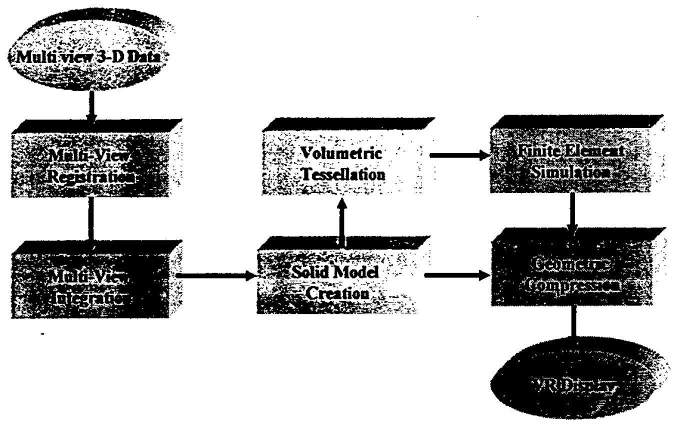
Surface Studio possesses a complete set of skin-based modeling tools and much more since it is an advanced modeling software.

GEOMETRIC ANALYSIS:

Surface Studio ensures that the model you created meets your specifications. A surface-to-cloud plot shows you exactly how much your model deviates from the collected data points, while surface continuity plots and virtual tube lights ensure the quality of your surfaced model.

NRC · CNRC

Virtualized Finite Element Analysis

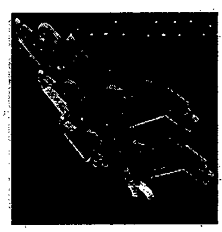


NRC · CNRC

Virtualized Finite Element Applied to Aluminum *Die-Casting*

Measured Data Points

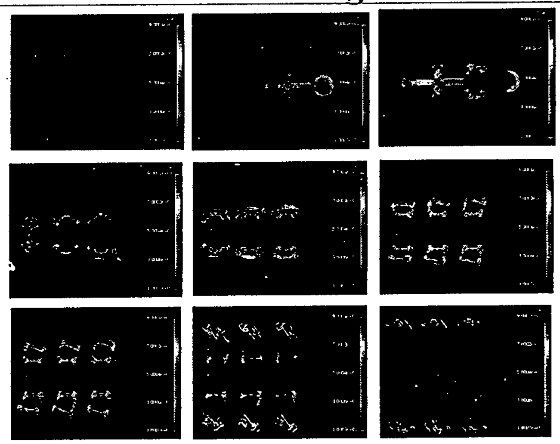
Constructed Model



Constructed Mould

NRC · CNRC

Virtualized Finite Element Applied to Aluminum Die-Casting



Flow of Aluminum in the die-cast mould NRC · CNRC

References

Roth, G., and Boulanger, P. CAD model building from multiple range images. Proceedings of Vision Interface 98. Vancouver, B.C. June 1998. pp. 274-281.

Godin, G., Soucy, M., and Boulanger, P. High-speed and non-contact validation of rapid prototyping parts. SPIE Proceedings, Rapid Product Development Technologies Boston, MA. November 18-19, 1996. Volume 2910. pp. 34-44.

Godin, G., Roth, G., and Boulanger, P. Using laser geometric sensing for rapid product development. Proceedings of the Intelligent Manufacturing Systems International Conference on Rapid Product Development, Stuttgart, Germany. January 31 - February 2, 1994. pp. 403-416.

Sekita, I., Boulanger, P., and Godin, G. Extraction and approximation of range image data using a rational Bézier surface. Proceedings of Vision Interface '93, Toronto, Ont. May 18-21, 1993. pp 77-83.

Boulanger, P., Godin, G., and Rioux, M. Application of 3-D active vision to rapid prototyping and reverse engineering. Proceedings of the Third International Conference on Rapid Prototyping, Dayton, OH. June 7-10, 1992. pp. 213-223.

NRC · CNRC

Subj. No. ______

NAME ______________________________ DATE ____/____/____

MALE ____ FEMALE ____

(Measurement Values in cm)

	Dimension	Value		Dimension	Value
1	Weight (Mass)				
			21	Thigh Circ. Max.	
2	Stature				
			22	Ankle Circ.	
3	Crotch Height				
			23	Foot Length	
4	Thumb Tip Reach - 1				
	Thumb Tip Reach - 2		24	Shoulder (Bideltoid) Breadth	
	Thumb Tip Reach - 3				
			25	Sitting Height	
5	Subscapular Skinfold	mm			
			26	Eye Height Sitting	
6	Triceps Skinfold	mm			
			27	Acromial Ht. Sitting	
7	Arm Length (Spine-Shoulder)				
			28	Elbow Height, Sitting (Rt)	
8	Arm Length (Spine-Elbow)				
			29	Knee Height Sitting	
9	Arm Length (Spine-Wrist)				
			30	Thigh Circ. Max Sitting	
10	Armscye Circ (Scye Circ/Acrom.)				
			31	Hand Circ.	
11	Chest Girth (Chest Circ at Scye)				
			32	Head Circ.	
12	Bust/Chest Circ.				
			33	Head Length	
13	Bust/Chest Circ. Under Bust				
			34	Bizygomatic Breadth	
14	Waist Circ., Preferred				
			35	Head Breadth	
15	Waist Height, Preferred (Rt)				
			36	Hip Breadth Sitting	
16	Waist Front Length				
			37	Buttock-Knee Length	
17	Total Crotch Length				
			38	Face Length	
18	Vertical Trunk Circ.				
			39	Hand Length	
19	Hip Circ., Maximum				
			40	Neck Base Circ.	
20	*Hip Circ., Maximum Ht.*				

Measurer ______________________

Recorder ______________________

LANDMARK DESCRIPTIONS AND COMPLIANCE

Landmark Naming Convention: Body Part, Directional information, Right and Left when both, (Alternate Name or Abbreviation)

Landmark Purpose Abbreviations: J = required for estimating joint centers; Sg = required for segmentation; C = required for segment-based coordinate systems; S = required for scanned anthropometry; T = required for traditional anthropometry.

No.	Landmark Name	Description	ISO 7250	SAE	ASTM D5219 or ASTM D5585	ASCC	Purpose
1	Acromion, Left and Right	The most lateral point on the lateral edge of the acromial process of the scapula; a point on the tip of the shoulder.	ISO 2.2.1	Yes	N/A	Yes	Left: J,Sg,C,S; Right: J,Sg,C,S,T
2	Axilla Point, Anterior; Left and Right	The lowest point on the anterior axillary fold (armpit). An adhesive dot is placed on the arm at the level of the lowest point on the axillary fold.	N/A	N/A	Yes (Front-Break Point)	Yes	Left and Right: Sg, S
3	Axilla Point, Posterior; Left and Right	The lowest point on the posterior axillary fold (armpit). An adhesive dot is placed on the arm at the level of the lowest point on the axillary fold.	N/A	N/A	Yes (Back-Break Point)	Yes	Left and Right: Sg, S
4	Calcaneus, Posterior; Left and Right[1]	The most prominent posterior point of the heel. Note: the most prominent point on the heel may be on the tissue, not necessarily on the Calcaneus bone.	N/A	N/A	N/A	N/A	Left and Right: C
5	Cervicale	The superior tip of the spinous process of the seventh cervical vertebra (the most prominent protrusion of the spinal column at the base of the neck).	ISO 2.2.5	Yes	Yes	Yes	J, Sg, C, S,T

[1] AFAMRL-TR-80-119 McConville, Churchill, Kaleps, Clauser, and Cuzzi. Anthropometric Relationships of Body and Body Segment Moments of Inertia, Dec. 1990.

6	Clavicale, Left and Right	The front of the most eminent prominence of the superior aspect of the medial end of the clavicale at the sterno-clavicular junction (at the "collar bone").	N/A	N/A	N/A	N/A	Left and Right: Sg,C
7	Crotch	A point calculated midway between the right and left trochanterion landmarks at the level of the crotch height as measured with the anthropometer.	N/A	N/A	N/A	N/A	J,C
8	Dactylion, Left and Right[1]	The tip of the middle finger. An adhesive dot is placed on the fingernail with the center of the dot corresponding to the tip of the finger.	N/A	Yes	N/A	N/A	Left and Right: C
9	Digit II, and Left Right[1]	The tip of the second toe. An adhesive dot is placed on the tip of the toe, not on the toenail.	N/A	No; this is the same as acropodion when the second toe is longer than the first.	N/A	N/A	Left and Right: C
10	Femoral Epicondyle, Medial; Left and Right	The medial point on the medial epicondyle of the femur. (The femoral epicondyles are marked while the subject is standing.)	N/A	Yes	N/A	Yes	Left and Right: J,C
11	Femoral Epicondyle, Lateral; Left and Right	The lateral point on the lateral epicondyle of the femur. (The femoral epicondyles are marked while the subject is standing.)	N/A	Yes	N/A	Yes	Left and Right: J,Sg,C
12	Glabella	Landmark title for the most forward (most protruding) point in the midline of the face (midsagittal plane) between the brow ridges.	N/A	N/A	N/A	N/A	T

13	Gonion, Left and Right[1]	The inferior posterior tip of the gonial angle; the posterior point on the angle of the mandible (the jawbone).	N/A	N/A	N/A	N/A	Left and Right: Sg
14	Humeral Epicondyle, Medial; Left and Right	The medial point on the medial epicondyle of the humerus, with the palm facing the side of the body.	N/A	Yes	N/A	Yes	Left and Right: J,Sg,C
15	Humeral Epicondyle, Lateral; Left and Right	The lateral point on the lateral epicondyle of the humerus, with the palm facing the side of the body.	N/A	Yes	N/A	Yes	Left and Right: J,Sg,C
16	Iliac Spine, Anterior, Superior; Left and Right (ASIS)[1]	The prominent anterior point on the anterior rim of the ilia. (The ilia are one of the three pair of bones that comprise the bony pelvis.)	N/A	Yes	N/A	N/A	Left and Right: J,Sg,C
17	Iliac Spine, Posterior, Superior; Left and Right (PSIS)[1]	The prominent point on the posterior superior spine of the ilium; a dimple often overlies this point. (The ilia are one of the three pair of bones that comprise the bony pelvis.)	N/A	N/A	N/A	N/A	Left and Right: J,C
18	Iliocristale, Left and Right[1]	The superior point of the iliac crest directly superior to trochanterion.	N/A	Yes	N/A	N/A	Left and Right: Sg
19	Infraorbitale, Left and Right[1]	The lowest point on the inferior margin of the orbit (the bony eye socket), directly inferior to pupil.	N/A	N/A	N/A	N/A	Left: C; Right: C,T
20	Knee Crease, Left and Right	The midpoint of the crease that runs medial to lateral on the posterior side of the knee. The knee crease is marked while the subject is standing.	N/A	N/A	Yes	N/A	Left and Right: S

21	Malleolus, Medial; Left and Right	The medial point on the distal tibial protrusion of the ankle.	N/A	Yes	N/A	N/A	Left and Right: J
22	Malleolus, Lateral; Left and Right	The lateral point on the distal fibular protrusion of the ankle.	N/A	Yes	N/A	Yes	Left and Right: J,C,S
23	Menton	Landmark title for the inferior point of the mandible (tip of the chin) in the midsagittal plane.	N/A	N/A	N/A	N/A	T
24	Metacarpal-Phalangeal II; Left and Right[1]	The prominent point on the lateral surface of the second metacarpal-phalangeal joint.	N/A	Yes	N/A	N/A	Left and Right: C
25	Metacarpal-Phalangeal V; Left and Right[1]	The medial prominent point on the medial surface of the fifth metacarpal-phalangeal joint.	N/A	Yes	N/A	N/A	Left and Right: C
26	Metatarsal-Phalangeal I; Left and Right[1]	The maximum protrusion of the inside of the foot at the head of Metatarsus I.	N/A	Yes	N/A	N/A	Left: C, S; Right: C, S,T
27	Metatarsal-Phalangeal V; Left and Right[1]	The maximum protrusion of the outside of the foot at the head of Metatarsus V.	N/A	Yes	N/A	N/A	Left: C, S; Right: C, S,T
28	Nuchale[1]	The lowest point of the occiput (in the midsagittal plane) that can be palpated among the nuchal muscles. This point is often visually obscured by hair.	N/A	N/A	N/A	N/A	C
29	Olecranon, Left and Right[1]	The posterior point on the olecranon process of the ulna, marked with the elbow bent 90 degrees.	N/A	No-arm is at 90 degrees.	Yes	N/A	Left and Right: Sg
30	Radial Styloid, Left and Right[1]	The point of the distal tip of the radius.	ISO 2.2.26	Yes	Yes	Yes	Left and Right: J, Sg,C,S

31	Radiale, Left and Right[1]	The highest point of the proximal head of the radius, near the midpoint of the elbow on the lateral aspect of the arm.	N/A	N/A	N/A	N/A	Left and Right: C,S
32	Sellion[1]	The greatest indentation of the nasal root depression in the midsagittal plane.	ISO 2.2.19	N/A	N/A	N/A	C,S,T
33	Sphyrion, Left and Right[1]	The distal point on the medial side of the tibia.	N/A	N/A	N/A	N/A	Left and Right: Sg, C,S
34	Substernale	The lowest palpable point on the sternum (breastbone).	N/A	N/A	N/A	N/A	S
35	Supramenton	The point of greatest indentation of the mandibular symphysis, marked in the midsagittal plane.	N/A	N/A	N/A	N/A	S
36	Suprapatella	The top of the kneecap; the superior point on the patella while it is in the relaxed (loose) position.	N/A	N/A	N/A	N/A	T
37	Suprasternale	The highest palpable point on the sternum (breastbone).	N/A	Yes	N/A	N/A	C,S
38	Tenth Rib, Left and Right[1]	The lowest palpable point on the inferior border of each Tenth Rib at the bottom of the rib cage.	N/A	Yes	N/A	N/A	Left and Right: Sg
39	Tenth Rib Midspine	A landmark located on the spine at the level of the right tenth rib landmark. The anthropometer is used to transfer the level of the landmark to midspine (on the spine in the midsagittal plane).	N/A	N/A	N/A	N/A	J,Sg,C
40	Thelion/Bust-point, Left and Right[1]	The most anterior protrusion of the bra cup on women; the center of the nipple on men.	N/A	Yes	Yes	N/A	Left and Right: S,T

41	Tragion, Left and Right[1]	Tragion corresponds (approximately) to the upper edge of the ear hole. Tragion is the superior point of the juncture of the tragus (cartilaginous flap of the ear) with the head.	ISO 2.2.30	N/A	N/A	N/A	Left: J,C; Right: J,C, T
42	Trochanterion, Left and Right[2]	The top of the bony lateral protrusion of the proximal end of the femur.	N/A	Yes	N/A	Yes	Left and Right: J, Sg,C,S
43	Ulnar Styloid, Left and Right[1]	The distal point of the ulna.	ISO 2.2.26	N/A	N/A	Yes	Left and Right: J, Sg,C
44	Waist, Preferred, Posterior	The preferred waist is the level of the waist established by the subject placing an elastic band where he or she would prefer to wear the waist of their pants. The landmark is located on the subject's back in the midsagittal plane.	N/A	Waist is defined as the midpoint of Iliocristale and Tenth Rib	Yes	N/A	S

[2] Hertzberg, H.T.E., Edmund Churchill, C. Wesley Dupertuis, Robert M. White, and Albert Damon. Anthropometric Survey of Turkey, Greece, and Italy, Advisory Group for Aeronautical Research and Development, Pergamon Press, New York, 1963.

Measurements Descriptions and Standards Compliance

No.	Name	Landmark	Description	ISO 7250	SAE	ASTM D5219/5585	ASCC
1	Acromial Ht. Sit.	Acromion, Right	The vertical distance is measured between the sitting surface and the right acromion landmark (the tip of the shoulder). The subject sits erect on a flat surface, looking straight ahead. The feet are supported. The thighs are parallel to each other, the feet are in line with the thighs, and the knees are bent 90°. The upper arms hang relaxed at the sides with the elbows bent 90° and the palms facing each other.	Yes	Yes	N/A	Yes
2	Ankle Circ.	Malleoli	The circumference of the ankle is measured across the maleoli landmarks (the two bony protrusions of the ankle). The subject stands erect with the weight distributed equally on both feet.	N/A	Minimum Circ	Yes	Min. Circ.
3	Arm Length (Shoulder-Elbow)	Acromion, Right; Olecranon, Right	While the subject is standing with the arm bent and the hand placed on the hip, the investigators measure the distance from cervicale landmark on the spine to the	N/A	N/A	Yes	N/A

			shoulder, from the cervicale landmark on the spine to the elbow, and from the cervicale landmark on the spine to the wrist. ***Shoulder-Elbow Length*** is calculated by subtracting the Spine-Shoulder Length measurement from the Spine-Elbow Length measurement.				
4	Arm Length (Shoulder-Wrist)	Acromion, Right; Ulnar Styloid, Right	While the subject is standing with the arm bent and the hand placed on the hip, the investigators measure the distance from the cervicale landmark on the spine to the shoulder, from the cervicale landmark on the spine to the elbow, and from the cervicale landmark on the spine to the wrist. ***Shoulder-Wrist Length*** is calculated by subtracting the Spine-Shoulder Length measurement from the Spine-Wrist Length measurement.	N/A	N/A	Yes	N/A
5	Arm Length (Spine-Wrist)	Cervicale, Right; Ulnar Styloid, Right	The distance is measured from cervicale, over the top of the acromion point, then along the outside of the arm to an elastic band worn around the wrist at the radial and ulnar styloid landmarks. The subject stands with the arm bent and the hand	N/A	N/A	Yes	N/A

			placed on the hip.				
6	Armscye Circ. (Scye Circ. over Acromion)	Acromion, Right	The distance from the shoulder down through the front-break point[1], the armpit, the back-break point[2], and to the starting point.	N/A	Yes	Yes	N/A
7	Bizygomatic Breadth	Zygion	The maximum horizontal distance is measured across the face between the zygomatic arches (cheekbones).	N/A	N/A	N/A	N/A
8	Bust/Chest Circ.	Thelion, Bustpoints	The circumference of the body is measured across thelion on men, or across the bustpoint landmarks on women. The circumference is measured parallel to the standing surface and is taken at the maximum point of quiet respiration.	Yes	Yes	Yes	Measured at mean point of quiet respiration
9	Bust/Chest Circ, Under Bust		On female subjects, the horizontal circumference of the chest is measured just below the cups of the bra. The circumference is measured parallel to the standing surface and is taken at the maximum point of quiet respiration.	N/A	N/A	N/A	N/A
10	Buttock Knee Lth.		The horizontal distance is measured between the most protrusive point of the right	Yes	Yes	N/A	Yes

[1] The location on the front of the body where the arm separates from the body.
[2] The location on the back of the body where the arm separates from the body.

			buttock and the most forward point of the right knee. The subject sits on a flat surface, looking straight ahead. The thighs are parallel to each other, the feet are in line with the thighs, and the knees are bent 90°.				
11	Chest Girth (Chest Circ. at Scye)		The maximum circumference of the body is measured over the shoulder blades, under the arms, and across the upper chest. The circumference is measured horizontal to the standing surface and is taken at the maximum point of quiet respiration.	N/A	N/A	Yes	N/A
12	Crotch Height		The vertical distance is measured from the standing surface to the lowest point of the crotch. The subject's feet are placed in footprints adhered to the standing surface (the footprints are positioned 10 cm apart at the heels and rotated 33° at the toes). The subject stands erect with the weight distributed equally on both feet.	Yes	N/A	N/A	N/A
13	Elbow Height, Sitting (Elbow Rest Height)	Olecranon, Right	The vertical distance is measured between the sitting surface and the olecranon	Yes	Yes	N/A	Yes

			landmark (at the bottom of the tip of the right elbow). The subject sits erect on a flat surface, looking straight ahead. The feet are supported. The thighs are parallel to each other, the feet are in line with the thighs, and the knees are bent 90°. The upper arms hang relaxed at the sides with the elbows bent 90° and the palms facing each other.				
14	Eye Ht. Sitting	Ecto-canthus, Right	The vertical distance is measured between the sitting surface and the right ectocanthus landmark (the outer corner of the eye). The subject sits erect on a flat surface, looking straight ahead. The feet are supported. The thighs are parallel to each other, the feet are in line with the thighs, and the knees are bent 90°. The upper arms hang relaxed at the sides with the elbows bent 90° and the palms facing each other.	Yes	Yes	N/A	Yes
15	Face Length (Menton-Sellion Length)	Menton, Sellion	The vertical distance is measured between the menton landmark underside of the tip of the chin in the midsagittal plane, and the sellion landmark	Yes	N/A	N/A	N/A

			(the greatest indentation of the nasal root in the midsagittal plane).				
16	Foot Length		The horizontal distance from the tip of the longest toe to the most protruding point on the back of the heel is measured parallel to the long axis of the foot. NOTE: Most protruding heel point is not necessarily the calcaneus.	Yes	N/A	N/A	Yes
17	Hand Circumference	Metacarpal-Phalangeal II, Right and Metacarpal-Phalangeal V, Right	The circumference of the right hand is measured across the Metacarpal-Phalangeal II and V with a tape passing across the sides of the knuckles of the second and little fingers at the points of their greatest indentation. The right hand is held palm down with the fingers together and straight and with the thumb away from the side of the hand.	N/A	Yes	N/A	Yes
18	Hand Length	Dactylion, Right; Radial Styloid, Right	The distance from the Dactylion landmark (the tip of the middle finger) to the elastic wrist band is measured parallel to the long axis of the hand. The right hand is held with the fingers together and straight.	Yes	Yes	N/A	Yes
19	Head Breadth		The maximum horizontal breadth of the head is measured	Yes	Yes	N/A	Yes

			above the ears.				
20	Head Circ		The maximum circumference of the head is measured perpendicular to its long axis of the head. in a front-to-back plane with the tape passing just above the bony brow ridges and across the most protruding point of the back of the head.	Yes	Yes	N/A	Yes
21	Head Length	Glabella	The maximum straight-line distance is measured between the glabella landmark (the most protruding point of the forehead between the brow ridges) and the most protruding point of back of the head.	Yes	Yes	N/A	Yes
22	Hip Breadth, Sitting		The maximum breadth of the hips or thighs is measured while the subject is sitting erect on a flat surface, looking straight ahead. The subject sits erect on a flat surface, looking straight ahead. The feet are supported. The thighs, knees, and feet are together (touching). The knees are bent 90°. The upper arms hang relaxed at the sides with the elbows bent 90° and the palms facing each other.	Yes	Yes	N/A	Yes
23	Hip Circumference,		The maximum hip circumference is measured	N/A	N/A	Yes (5585)	N/A

	Maximum		parallel to the standing surface.				
24	Hip Circumference Max Ht.		The vertical distance is measured from the standing surface to the level of the maximum Hip Circumference in the right mid-lateral line. The subject's feet are placed in footprints adhered to the standing surface. The subject stands erect with the weight distributed equally on both feet.	N/A	N/A	Yes	N/A
25	Knee Ht. Sitting	Supra-patella, Right	The vertical distance is measured between the surface of the foot support and the suprapatella landmark at the top of the right knee. The subject sits erect on a flat surface, looking straight ahead. The feet are supported. The thighs are parallel to each other, the feet are in line with the thighs, and the knees are bent 90°.	Yes	N/A	N/A	Yes
26	Neck Base Circ.	Cervicale	The circumference of the base of the neck is measured across the cervicale landmark at the juncture of the neck and the shoulders.	N/A	N/A	Yes (5585)	N/A
27	Shoulder Breadth (Bideltoid Brth.)		The distance is measured between the maximum lateral protrusions of the right and left	Yes	Yes	N/A	N/A

			deltoid muscles. The arms hang relaxed at the sides.				
28	Sitting Height		The vertical distance is measured between the sitting surface and the top of the head. The subject sits erect on a flat surface, looking straight ahead. The feet are supported. The thighs are parallel to each other, the feet are in line with the thighs, and the knees are bent 90°. The upper arms hang relaxed at the sides with the elbows bent 90° and the palms facing each other.	Yes	Yes	N/A	Yes
29	Stature		The vertical distance is measured between the standing surface and the top of the head. The subject feet are placed in footprints adhered to the standing surface. The arms are relaxed at the sides and the weight is distributed equally on both feet.	Feet are together	Feet are together	Yes	Feet are together
30	Subscapular Skinfold		The thickness of a diagonal fold of skin and tissue (fat) is measured just below the tip of the right scapula (shoulder blade). The subject stands with the shoulders and arms relaxed.	N/A	N/A	N/A	N/A
31	Thigh Circumference,		The maximum circumference of the right thigh is measured.	Yes	N/A	Yes	N/A

	Maximum		The maximum is established by placing the tape measure around the thigh at its proximal end (at the thigh/buttock juncture) and moving the tape measure down the thigh in one-centimeter increments until the maximum circumference is reached. NOTE: The maximum circumference may exist at the thigh/buttock juncture.				
32	Thigh Circ. Max., Sitting		The maximum circumference of the right thigh is measured on a seated subject. The maximum circumference is established by placing the tape measure around the flattened thigh at its proximal end (at the thigh/buttock juncture) with the tape measure held perpendicular to the sitting surface. The max circumference is established by moving the tape measure down the thigh in one-centimeter increments until the maximum thigh circumference is found. The subject sits erect on a flat surface with the entire upper leg resting on the flat surface and the lower leg dangling. NOTE: The maximum	N/A	N/A	N/A	N/A

			circumference may exist at the thigh/buttock juncture; however, on some subjects the tape measure may not be perpendicular to the sitting surface in this case the initial circumference would be more distal than the thigh/buttock juncture.				
33	Thumb Tip Reach		The subject stands with the shoulders and back against the wall. The heels are 10 centimeters from the wall, approximately shoulder-width apart. The right arm is extended forward with the index finger and thumb touching. The arm is held perpendicular to the wall and horizontal.	N/A	N/A	N/A	Yes
34	Total Crotch Length (Crotch Lth.)		The measurement is taken from the anterior preferred waist, through the crotch to the Preferred Waist, Posterior landmark. The anterior preferred waist is a point on the subject's abdomen at the level of the preferred waist in the midsagittal plane. The subject's feet are placed in footprints adhered to the standing surface. The subject stands erect with	N/A	N/A	Yes	N/A

			the weight distributed equally on both feet.				
35	Triceps Skinfold		The thickness of a vertical fold of skin and tissue (fat) is measured on the back of the right upper between the tip of the shoulder and the elbow while the subject's arm is bent 90°.	N/A	N/A	N/A	N/A
36	Vertical Trunk Circ.		The distance measured from a point on the right shoulder midway between the neck base and the shoulder joint, down the back, through the crotch, and right bust point or thelion landmark, to the starting point. Care must be taken to avoid constriction in the crotch.	N/A	N/A	Yes	Yes
37	Waist Circ. Preferred		The circumference of the waist is measured at the level of the subject's "preferred" waist as established by the placement of an elastic waist belt.	N/A	N/A	Yes	N/A
38	Waist Front Length		The distance from a point on the front of the neck at neck base in the midsagittal plane is measured to the anterior preferred waist.	N/A	N/A	Yes	N/A
39	Waist Height, Preferred		The vertical distance is measured on the subject's right side, from the standing surface to the level of the preferred	N/A	N/A	Yes	N/A

			waist at the center of the elastic waist band. The subject's feet are placed in footprints adhered to the standing surface. The subject stands erect with the weight distributed equally on both feet.				
40	Weight (Mass)		The weight of the subject is measured as the subject stands on the scale clad in CAESAR garments with the weight distributed equally on both feet.	N/A	Yes	N/A	Yes